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# **SHORE PLATFORM PROCESSES IN EASTERN CANADA**

By  
Neil James Porter

A Thesis  
Submitted to the Faculty of Graduate Studies and Research  
through Earth Sciences  
in Partial Fulfillment of the Requirements for  
the Degree of Master of Science at the  
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## ABSTRACT

This study examines the erosional processes operating on horizontal and sloping shore platforms in eastern Canada. About 110 traversing micro-erosion meter (TMEM) stations were installed in three areas. TMEM downwearing data in basalts, argillites, and sandstones by wetting and drying and salt weathering have been supplemented with data obtained from tidal simulators in the laboratory. Downwearing rates, measured over periods from 1 to 3 years, generally ranged between 0 and several mm yr<sup>-1</sup>. Erosion rates generally increase towards the upper intertidal zone in fresh water and artificial sea water. Rock surface expansion and contraction owing to water uptake and loss were measured through tidal cycles in the field and in the laboratory. The data suggest that downwearing by weathering and backwearing by waves are both important on shore platforms, though there are temporal and spatial variations in their absolute and relative significance.

Keywords: shore platforms; traversing micro-erosion meter; wetting and drying; salt weathering; tides.

## CO-AUTHORSHIP STATEMENT

Included in this thesis are two manuscripts formatted to thesis requirements:

1. The manuscript entitled “Shore Platform Processes In Eastern Canada” is in press with the journal *Geographie Physique et Quaternaire*. The paper is co-authored by Trenhaile, A.S., Porter, N.J. and Kanyaya, J.I. and appears in chapter 2.
2. The manuscript entitled “Short-term rock expansion and contraction in the intertidal zone” was submitted to the journal *Earth Surface Processes and Landforms*. The paper is co-authored by Porter, N.J., and Trenhaile, A.S. This manuscript appears in chapter 3.

The study was directed by A.S. Trenhaile, who also contributed to the data interpretation and drafting of the manuscripts. N.J. Porter and J.I. Kanyaya were largely responsible for data collection, and both contributed to the data analysis and interpretation. N.J. Porter was also responsible for presenting the findings and drafting the thesis manuscripts.

## **DEDICATION**

I dedicate this work to my mother, Carmen.

## **ACKNOWLEDGEMENTS**

I would like to express my appreciation to all those people who have aided me during the course of my research. In particular, I would like to extend a special thank you to my advisor, Dr. Alan Trenhaile, for all the support he provided me during the past two years. By far the most understanding and supportive advisor anyone could ask for. In addition, special thanks go out to Dr. Eric Mattson, Dr. John Kovacs and Dr. Jaime LeClair (Nipissing University) who were responsible for my inspiration to succeed to the Master's level.

I would also like to acknowledge my appreciation to Shanmugam Johari Pannalal, Jacob Kanyaya, Juan Carlos Ordonez-Calderon, Steven Rozic and Kaiguang Zhu for all the technical advice and friendship; thanks guys, I owe you one! Finally, I would like to express my sincerest thanks to Sharon Horne. Thanks for all the insider information and allowing me to participate in your skulduggery activities. You got me in, and out of trouble a few times.

## **STATEMENT OF ORIGINALITY**

“I certify that, this thesis, and the research to which it refers, are the product of my own work, and that the ideas or quotations from the work of other people, published or otherwise, are fully acknowledged in accordance with the standard referencing practices of the discipline. I acknowledge the helpful guidance and support of my supervisor, Dr. A.S. Trenhaile”.



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# CHAPTER 1

## Introduction, literature review and objectives

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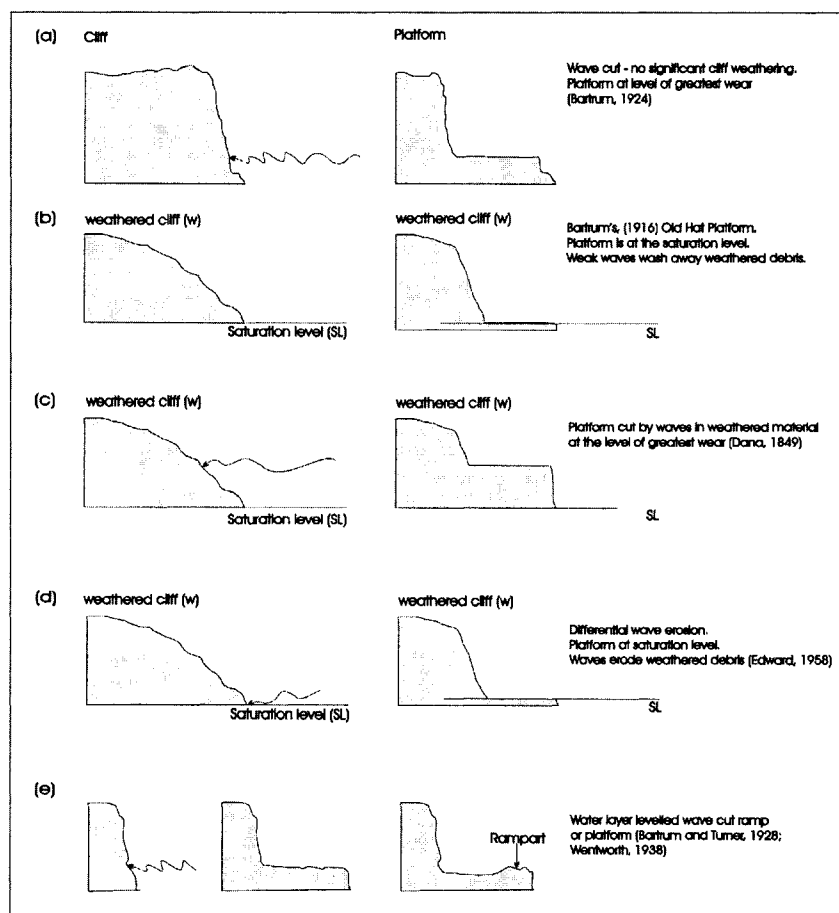
### 1.0 Introduction

Shore platforms are gently sloping to subhorizontal rock surfaces extending seawards, in some cases for hundreds of metres, from the cliff foot. They are conspicuous elements of rocky coasts in environments ranging from the poles to the tropics. Most shore platforms are essentially intertidal and although they are produced by the retreat of coastal sea cliffs, the processes responsible for cliff erosion and platform lowering may be quite different in type and/or intensity from one platform to the next.

Earlier research regarding shore platforms was mainly descriptive (Trenhaile, 1987), and because of the absence of almost any process measurements, arguments over the formative processes, which began in the late 19<sup>th</sup> century, have been largely based on ambiguous field evidence. As a result, genetic terminology, such as “wave cut platforms” (Bradley, 1958; Edwards, 1958; King, 1963; Sorensen, 1968; Bradley and Griggs, 1976; Sparks, 1986); “benches” (Zenkovich, 1967); “abrasion platforms” (Johnson, 1919); and “storm wave platform” (Edwards, 1941) were common in the literature. Unless the responsible processes have been identified, these terms should not be used because of their genetic connotation, which implies that specific processes are responsible for platform formation. Much of the research on shore platforms has, until the last few decades, been conducted by Australasian researchers, and their depictions and interpretations have had a strong influence on the literature for nearly a century. Weathering is generally thought to play an important role in the development of sub-horizontal shore platforms in Australasia and in other swell- to low-wave energy environments (Wentworth, 1938, 1939; Hills, 1949, 1971; Gill, 1967, 1972; Bird, 1968; Davies, 1972; Stephenson and Kirk, 2000). Nevertheless, some workers have argued that waves are the main erosive mechanism on these platforms (Bartrum, 1924, 1935, 1938; Johnson, 1933; Jutson, 1931a,b, 1939; Edwards 1941, 1951). Waves have generally been assumed to be the dominant erosive agent on the sloping platforms around the coasts of the stormy North Atlantic (Johnson, 1919; Everard *et al.* 1964; So, 1965; Trenhaile, 1972, 1974, 1978; Sunamura, 1978).

## 2.0 The “wave versus weathering” debate

The mode of development of shore platforms has been disputed for over a century; the debate is focused on the premise that platform formation is the result of either wave erosion or sub-aerial processes. Dana (1849) first proposed that platforms are cut by waves from coastal cliffs at a level of maximum wear. Bartrum (1916) attributed the development of “Old Hat” platforms in sheltered environments, not to wave erosion at the level of greatest wear, but to weathering of cliffs down to an intertidal level at which the rocks are permanently saturated with sea water; the role of the weak waves being simply to wash away the fine, weathered debris. Bartrum also believed that horizontal “storm wave” platforms developed through wave erosion in more exposed environments (Bartrum 1935, 1938). Many of the earlier theories of platform development have been focused around, and modified from, Dana’s and Bartrum’s models (Fig. 1.1).



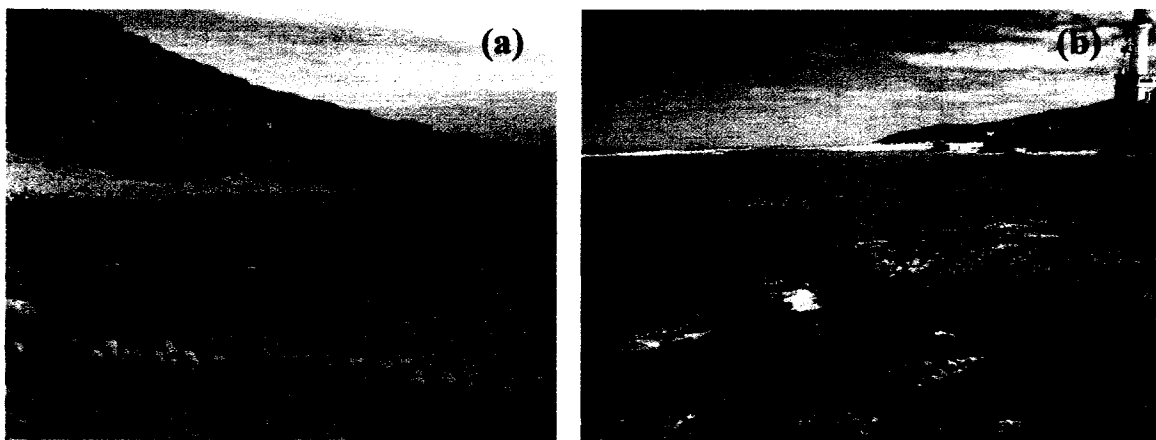
**Figure 1.1.** Theories for horizontal platform development (from Trenhaile 1987).

Although these theories formed the basis of early thinking, the weathering vs. wave erosion debate is misleading because the two types of platform, even if such pure forms actually exist, would represent only the two extremes of a spectrum of platform types in which both waves and weathering assume variable roles according to the morphogenic environment (wave climate, tides, etc) and the type of rock (Trenhaile, 1987).

Contemporary theories have emphasized that shore platforms are the result of both marine and sub-aerial processes. Waves may be the dominant process in some areas, or at some stage in the development of a platform, providing the energy to pluck material from cliffs and platforms (wave quarrying) and to move loose abrasives over the platform surface. However, weathering, which includes wetting and drying, salt weathering, frost action and chemical weathering, often plays an important role in wave-dominated environments, weakening the rocks and making them more susceptible to wave erosion. In other areas, or at other times, weathering may be dominant, and the role of waves and currents may be primarily to entrain and carry away the loose material.

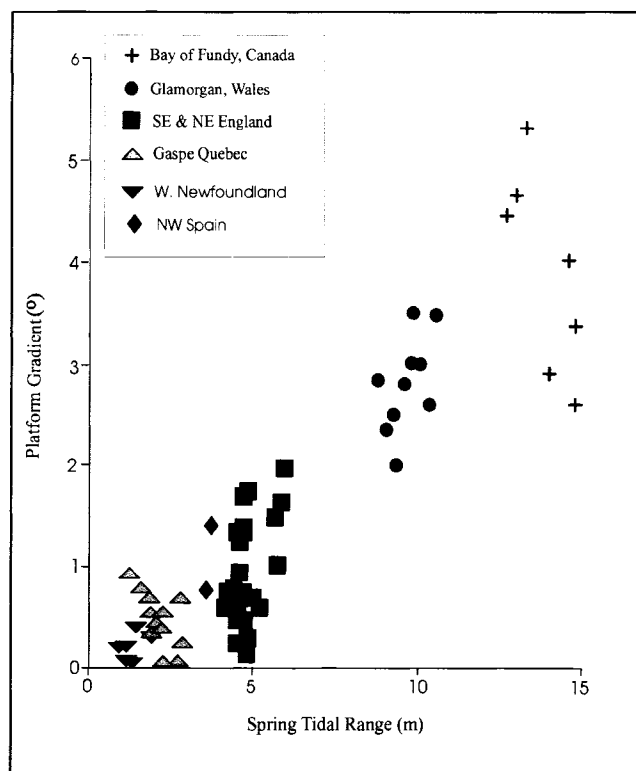
### 3.0 Shore platform morphology

Shore platforms are usually characterized by one of two distinct morphologies: (a) sloping platforms which have been called ramps, have gradients between  $1^\circ$  and  $5^\circ$ , and extend from the cliff – platform junction (cliff foot) to below the low tidal level, without any marked break in slope (other than those that are obviously attributable to structural or lithological factors); and (b) horizontal platforms generally terminate abruptly in a low tide cliff or ramp (Fig. 1.2).



**Figure 1.2.** a) sloping liassic limestone and shale platform in the Vale of Glamorgan, south Wales, UK; and b) horizontal aeolianite platform with a low tide cliff near Lonsdale, southern Victoria, Australia.

Although a few workers made some brief speculative comments on the possible effect of tidal range on platform morphology (Edwards, 1941; King, 1959; Gill, 1967; Wright, 1967; Davies, 1972), this factor was largely overlooked as a primary explanation for regional differences in platform morphology (Trenhaile, 1978). Trenhaile (1972, 1974, 1978, 1987, 1997, 2002, 2003) investigated the role of tidal range using data from south Wales (UK), southern Japan, eastern Canada, NE and SE England and NW Spain. He found a moderately strong positive relationship between shore platform gradient and tidal range (Fig. 1.3), which suggests that tidal range, rather than climate and wave conditions, is the main reason for the occurrence of horizontal platforms in the low tidal range environments of Australia and New Zealand, and sloping platforms in the high tidal range environments of the North Atlantic (Trenhaile, 1999). In eastern Canada, there are horizontal platforms in Gaspé, Québec, where the tidal range is between 2.25 and 3.5 metres (Trenhaile, 1987), and sloping platforms in the Bay of Fundy, where the tidal range is between 12 to 16 metres (Trenhaile, 2004). Trenhaile (1999) also demonstrated that platform width is independent of tidal range, but increases with wave intensity and decreases with rock resistance. Within areas that have an essentially common tidal range, there is a tendency for platform gradient to also increase with the strength of the rock (Trenhaile, 1972, 1978; Kirk, 1977; Sunamura, 1992).



**Figure 1.3.** The relationship between mean regional shore platform gradients and spring tidal range (Trenhaile, 2003).

#### 4.0 Wetting and drying weathering

Exposed rock surfaces are subjected to repeated cycles of wetting and drying in many natural environments. Alternate wetting and drying can cause rocks to weather through the absorption and adsorption of water. Absorbed water essentially flows, drains or is sucked into the rock, whereas adsorbed water can be attracted directly into the rock from humid air: this is largely the result of electrostatic charges, involving the positive ends of water molecules and the negative edges of clay particles in the rocks. Rock breakdown by wetting and drying depends on its lithology and internal characteristics, including the presence of clay minerals, cleavage planes and pore and capillary size (Bland and Rolls, 1998). Shales and other argillaceous rocks with high clay content are more susceptible than most other rocks to expansion and contraction due to alternate wetting and drying cycles. Other rock types that have no clay content, however, can also be affected by the wetting and drying process (Nishioka and Harada, 1958; Nepper-Christensen, 1965; Hudec and Sitar, 1975; Felix, 1983; Hamès *et al.*, 1987).

Although many processes contribute to the lowering of platform surfaces, it is generally assumed that alternate wetting and drying plays an effective role (Stephenson and Kirk, 2000; Trenhaile and Kanyaya, 2004). Many of the earlier Australasian investigations suggested that platforms are produced through weathering down to an intertidal level of permanent sea water saturation (Bartrum, 1916; Edwards, 1958; Bird and Dent, 1966; Gill, 1967). This is contrary to field and laboratory observations by Trenhaile and Mercan (1984), who demonstrated that there is no permanent saturation level within the intertidal zone.

Numerous investigations have been conducted to determine the effectiveness of wetting and drying on various types of rock. Goudie (1974) subjected sandstone and chalk to 58 and 43 alternate wetting and drying cycles, respectively, but he found no evident breakdown. Hall and Hall (1996) exposed sandstone and dolerite to 140 wetting and drying cycles, and found that wetting and drying can work independently of other physical processes. Many earlier laboratory investigations found that alternate wetting and drying is not an effective weathering mechanism, but this conclusion was derived primarily from experiments that had a fairly low number of cycles. Although wetting and drying can operate as an independent process, limited data have been obtained from the inter-tidal zone, which must offer almost optimum conditions for its operation. Stephenson and Kirk (2000) proposed that a mudstone shore platform on the Kaikoura Peninsula in southern New Zealand was produced entirely by weathering, especially by wetting and drying, and they suggested that wetting and drying was most effective at elevations which have the greatest frequency of tidal cycles. Trenhaile and Kanyaya (2004) set up a series of

laboratory tidal experiments to closely imitate natural wetting and drying cycles in the inter-tidal zone. Using artificial tidal simulators they subjected hundreds of sandstone, basalt, and argillite samples from shore platforms in eastern Canada to more than 1000 tidal exposure and inundation cycles over 18 months (these experiments are ongoing). Downwearing data were recorded for different rock types at different elevations within the intertidal zone. Kanyaya and Trenhaile (2005) found that the efficacy of wetting and drying varies throughout the intertidal zone, and is dependent more upon the length of the period of drying during low tide, than on the period of absorption during high tide. In general, wetting and drying efficacy increases towards the upper portions of the intertidal zone, where the rocks have more time to dry when they are exposed to the air than at lower elevations.

## **5.0 The expansion and contraction of rock surfaces**

It is generally accepted that expansion and contraction of rock surfaces under wetting and drying conditions is due to the absorption and adsorption of water. Although this process is not fully understood, it must be closely related to the characteristics of the rock, such as its permeability, porosity and mineral composition. Water can infiltrate or be adsorbed by rocks through fine cracks or between mineral grains. Water is usually drawn into fine cracks due to its bipolar nature. When cracks become wetted, the polar molecules are attracted to it, making a layer of adsorbed water. This layer will create swelling pressures within the crack, and as evaporation takes place, the sides may become drawn together by water molecules from adjacent sides (Bland and Rolls, 1998). Repeated cycles of wetting and drying eventually attack the unstable mineral grains and in some circumstances, repeated expansion and contraction cycles produce flaking of the rock surface.

Although many researchers have discussed the expansion and contraction of rock surfaces, the development of the MEM (micro-erosion meter), which was introduced by High and Hanna (1970), has made it possible to measure small variations in rock surface elevation in the laboratory and in the field. A micro-erosion meter consists of a simple engineer's dial gauge, affixed to a probe, which is mounted on a triangular frame. In use, this assembly is mounted upon three bolts that have been sunk and permanently embedded in the rock (a MEM station): this allows repeated measurements to be made at precisely the same place on a rock surface at regular intervals. The MEM only permits three measurements to be made at each station but the traversing MEM (TMEM) employs a series of ball-bearings that are fixed along each side of the base of the instrument to allow many measurements to be made (Trudgill *et al.*, 1981;

Stephenson, 1997; Stephenson *et al.*, 2004). Micro-erosion meters allow precise measurement of downwearing rates on rock surfaces. They have been applied to various problems, including the measurement of downwearing rates on shore platforms (Robinson, 1977a,b; Kirk, 1977; Gill and Lang, 1983; Mottershead, 1989; Stephenson and Kirk, 1996, 1998; Foote *et al.*, 2001; Andrade *et al.*, 2002, Trenhaile and Kanyaya, 2004).

Downwearing rates have been measured on shore platforms with MEMs and TMEMs for nearly thirty years, although most records are only 1 to 3 years in length. Many investigations have reported downwearing rates on the surface of shore platforms, but only a few researchers have observed surface “swelling” (Kirk, 1977; Mottershead, 1989; Stephenson and Kirk, 1998, 2001). A few researchers regarded the “swelling” or rising phenomena to be due to operator or instrument failure. Kirk (1977) first observed surface swelling on mudstone shore platforms on the Kaikoura Peninsula in southern New Zealand. He attributed the rise of 3 mm in elevation to a combination of algae growth and wetting of the mudstone. Further investigation of the same shore platforms showed that expansion and contraction varied on a seasonal basis (Stephenson and Kirk, 1998), and it was proposed that salt crystal growth between the rock lattices and expansion due to wetting and drying, particularly in response to higher summer temperatures, was mainly responsible. Swelling of up to 9 mm has been observed in some extreme cases (Stephenson and Kirk, 2001). Mottershead (1989) observed mean surface swelling of 0.04 mm on greenschists in southern Devon, England. He concluded that the swelling was due to salt weathering, but although salt weathering is likely to be effective in the higher temperatures of summer, the data showed no clear seasonal pattern.

Trenhaile (2006) conducted a series of short-term expansion and contraction experiments on sandstone, argillite and basalt slabs representing rock types from three shore platform study areas in eastern Canada. These expansion and contraction experiments were subjected to tidal conditions in de-ionized water and to a variety of humidity and temperature variations. He found that the sandstones (from Burntcoat Head, NS) did not expand or contract with the absorption or adsorption of water nor, except in a very small number of cases, did they expand or contract owing to variations in temperature and humidity. He concluded that the porous nature of the sandstone was sufficient to absorb water without generating any expansive pressures. The argillite sample (from Mount Louis, Gaspé, PQ) was much more sensitive to tidally induced expansion and contraction and temperature/humidity variations. Much of the surface contracted during the drying process when the rock was exposed, and it usually continued to contract until wetting began again in the tidal cycle ended. Argillites under tidal conditions contracted between 0.05 to 0.1 mm and by an average of 0.1 mm when exposed to variations in humidity of between

30 to 100%. In some cases the argillites expanded under warm conditions. Trenhaile concluded that the sensitivity of the argillites to fluctuating environmental conditions is a result of their high clay content, and their ability to absorb water when they are inundated by the tides and to adsorb water from humid air when they are exposed by the tides. A basaltic rock sample (from Scots Bay, NS) also contracted, typically between 0.01 to 0.02 mm, as it dried during low tidal periods. Whereas the argillite continued to contract during the entire period of exposure, the basalt had usually attained its maximum contraction after 6 hours drying. There were also slight variations in response to changes in temperature or humidity.

## **6.0 The effect of salt**

The effect of salt on rock breakdown has been a cause of concern for the past 2000 years (Goudie, 1985). Extensive field and laboratory experiments, especially by French geomorphologists in the 1950's and 1960's, illustrated the effects of various salts on different rock types (Biro, 1954; Pedro, 1957; Tricart, 1960). Salts are chemical compounds which are produced between acids and bases, with water as a by-product (Bland and Rolls, 1998). Many salts are water soluble, and for salts to be effective weathering agents they must be in the form of a solution that can travel within the pores of the rock. The rate at which solutions can penetrate rocks is primarily controlled by factors such as porosity (volume of pore space), micro-porosity (proportion of micro-pores), water absorption capacity (amount of water absorbed in a specific time) and saturation coefficient (amount of water absorbed in 24 hours, when sample is immersed)(Trenhaile, 1987; Bland and Rolls, 1998).

The primary concern is with the physical effects of salt solutions entering rock pores and cracks. Salts contribute to rock breakdown in three ways (Cooke and Smalley, 1968):

- 1) by changes in the volume of a salt crystal, due to hydration;
- 2) by thermal expansion of salt crystals; and
- 3) by salt crystal growth due to the evaporation and concentration of solutions.

There have been numerous field and laboratory experiments on the efficacy of salt weathering on various rock types. Some of the earliest research began with laboratory experiments which focused on the rate of disintegration of different sizes and shapes of samples (Goudie, 1974; Robinson and Williams, 1982) and on the role of different salts on different types of rock (Pedro, 1957; Kwand, 1970; Goudie *et al*, 1970; Goudie, 1974, 1985; Williams and



Robinson, 1981, 2001). Nevertheless, few experiments have satisfactorily simulated natural conditions (McGreevy and Whalley, 1984).

Visible signs of salt weathering are evident in coastal environments. Usually precipitated by sea spray, salt crystals can form in between rock lattices or in pore spaces, causing the rock to separate. Evidence of this phenomenon can be viewed as pitting or flaking on the surface of coastal rocks, particularly during warmer seasons (Stephenson and Kirk, 2001). Although there is a moderate body of literature on salt weathering in coastal environments, few researchers have considered its role in the development of shore platforms (Williams and Robinson, 1981). Mottershead (1982) examined the role of salts on shore platforms consisting of greenschist in southwestern England. By calculating the pressure of crystal growth within the pores, he determined that salt concentrations of 1.5% above that of sea water was sufficient to cause rock failure.

## **7.0 Purpose and objectives of the research**

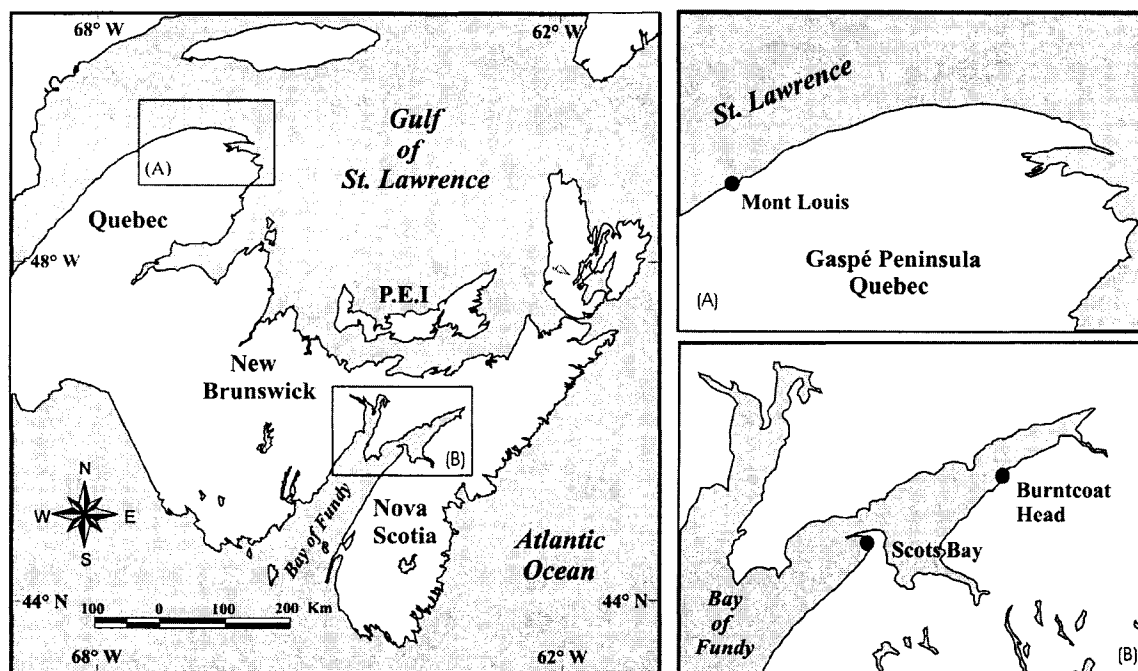
This research will contribute to an on-going investigation of the processes and evolution of sloping shore platforms in high tidal range environments and horizontal shore platforms in low tidal range environments. My study is primarily concerned with the absolute and relative rates of weathering and erosion resulting from intertidal wetting and drying and salt weathering. The specific objectives of the study are:

1. to measure rates of rock surface downwearing at various intertidal elevations owing to the effect of wetting and drying and salt weathering; and
2. to compare these downwearing rates with measured rates of platform downwearing in the field.

The investigation will have three main components: (a) continuing and extending Trenhaile and Kanyaya's laboratory experiments to measure wetting and drying and salt weathering downwearing rates in the laboratory; (b) measuring surface expansion and contraction in the laboratory and in the field; and c) measuring platform downwearing rates in three study areas using a transverse micro-erosion meter (TMEM).

## 8.0 Study areas

Eastern Canada probably has the greatest variety of tidal environments in the world, and it may consequently be one of only a very few areas that have both regionally dominant horizontal and sloping shore platforms. The three study sites represent a range of tidal environments and rock types: a meso-tidal horizontal platform at Mont Louis, Québec; a macro-tidal, sloping platform at Scots Bay, Nova Scotia; and a macro-tidal sloping platform at Burntcoat Head, Nova Scotia (Fig. 1.4).

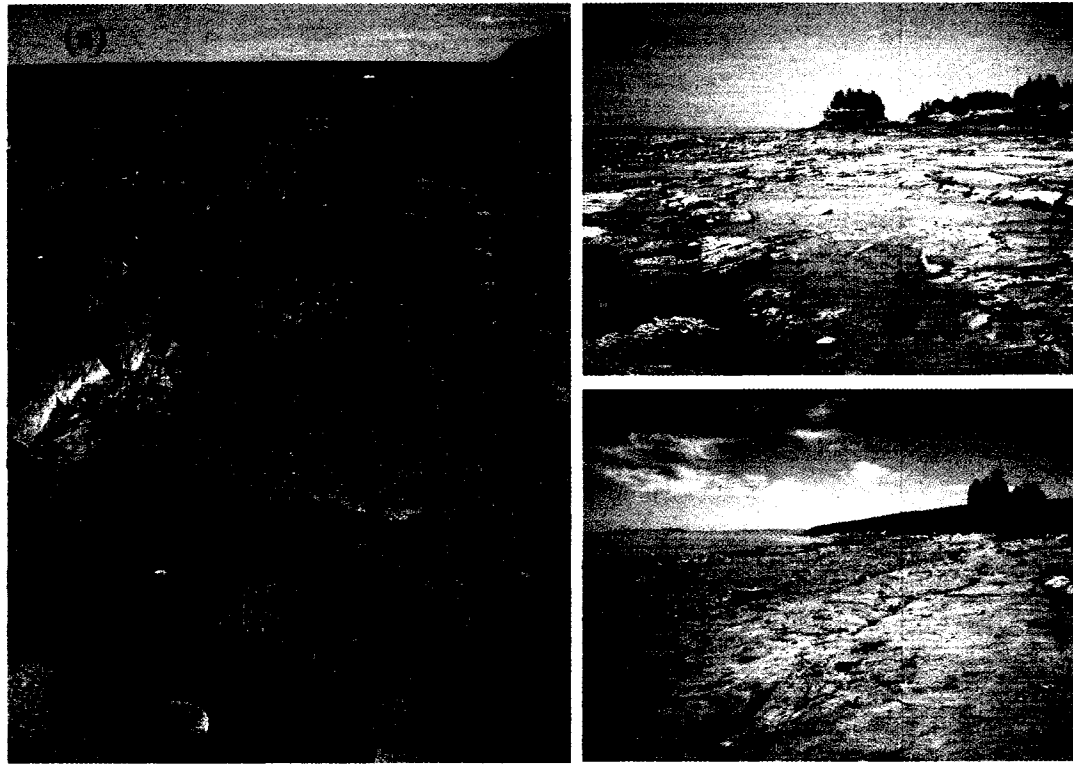


**Figure 1.4.** Study areas in eastern Canada

The Canadian Appalachian region includes the provinces of Nova Scotia, New Brunswick, Newfoundland, Prince Edward Island, and the southern regions of Québec. It experienced numerous rifting and faulting events associated with the Paleozoic Appalachian orogen, and the rocks in this region were subjected to extreme folding, faulting, metamorphism and plutonism (Williams, 1995). The orogen began with the opening and closing of the Paleozoic Iapetus Ocean, resulting in sedimentary strata either being subducted or heavily folded during continental collisions (Williams, 1995). Some of the oldest Paleozoic metamorphic rocks in Canada are found along the southern shore of the St. Lawrence River.

There are horizontal shore platforms along approximately 600 km of the southern shore of the St. Lawrence River, between Québec City and Cap-des-Rosiers (Trenhaile, 1978). Parautochthonous flysch in the Mont Louis region belongs to the Ordovician Cloridorme

formation (Williams, 1995) and is characterized by extreme folding and tectonic metamorphism.



**Figure 1.5.** (a) Horizontal metamorphic argillite platform at Mont Louis, Quebec; (b) Sloping red sandstone at Burntcoat Head in the Minas Basin; and (c) Sloping basaltic platform at Scots Bay in the Bay of Fundy.

The shore platform at Mont Louis primarily consists of dark grey argillites, with graywackes, interbedded shales, and calcite intrusions (Enos, 1969). The shore platform is elevated approximately 1 metre above the mid-tidal level and it ends abruptly seawards at a low tide cliff of unknown height. The platform is about 170 to 200 m wide and it is backed by a 3 to 4 meter high cliff, composed of the same lithology as the platform. There is a coarse-grained beach at the cliff foot. The platform surface is characterized by ridges of dipping argillite and other rocks with extensive pools between (Fig. 1.5). These pools persist during low tidal periods and sustain small pockets of flora and fauna. Eroded material accumulates in these pools where it cannot be washed away by tides or waves.

The waves along the Gaspé coast usually approach from a westerly or northwesterly direction, depending on seasonal variations. Nearly half of the waves in this region (41%) are less than 1 metre in height and only a small fraction (6%) reach heights of 3 metres during stormy

weather events. During the winter season, much of the coastline is protected by sea ice, which acts as a barrier to the waves (Eid *et al.*, 1991).

The red clastic sandstones at Burntcoat Head in the Bay of Fundy belong to the Triassic Wolfville Formation, which has been interpreted as being alluvial fan deposits (Klein, 1962). The highest tides in the world occur at Burntcoat Head: the largest recorded tidal range is more than 16 m, but average tidal ranges are between 12 and 14 m (Trenhaile, 2004). A wide shore platform runs along much of the southern shore of the Minas Basin. It is slightly concave upwards with an overall gradient between 3° and 4° (Trenhaile and Kanyaya, 2004) (Fig. 1.5) and is between 375 and 450 m in width. There are undulating areas of more resistant sandstone on the platform in places and stratified rock layers of rounded pebbles deposited by fluvial processes. There are large numbers of glacial erratics on the platform within the inter-tidal zone, many of large size; these erratics probably fell from the cliff top as the cliff was undermined by erosion. Most of the surface of the platform has few marine organisms (mainly restricted to gastropods and seaweed in the upper foreshore), although there are a variety of borers and burrowers in some large pools, and an almost continuous cover of barnacles on the rock surface near the low tidal level. Waves enter the Minas Basin from the southwest, west and northwest. The Minas Basin is quite sheltered, however, and the majority of waves (78%) are less than 1 metre in height (Eid *et al.*, 1991).

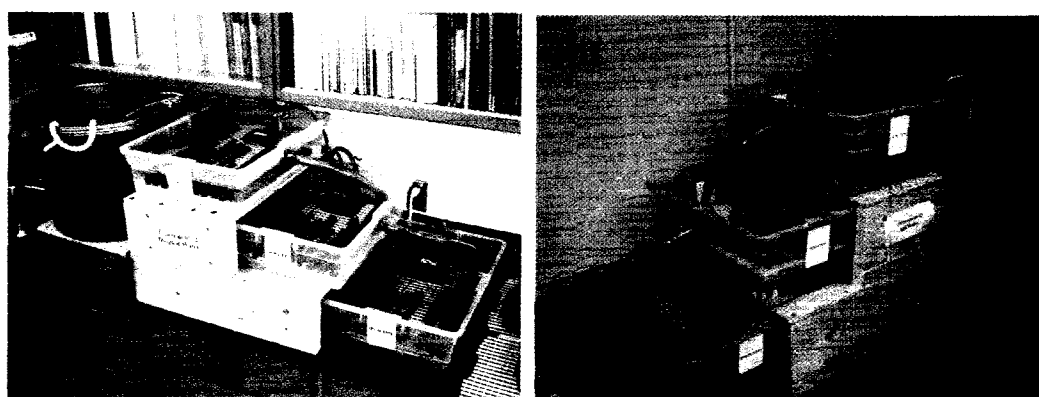
The third study area is at Scots Bay in the Bay of Fundy, in the Triassic North Mountain Basalts. Weaker basaltic surface features in this area are reinforced by resistant amydules, primarily composed of calcite and minerals from the zeolite family (Colwell, 1980). The shore platform is concave upwards, with a gradient of 7.5° in the upper part, 4.25° in the centre, and 3.5° in the lower segment (Trenhaile and Kanyaya, 2004) (Fig.1.5). The platform is approximately 100 to 120 m in width. The upper portion of the platform, above the neap high tidal level, is discoloured and extremely weathered. Lower segments of the platform contain an assortment of smaller, rounded boulders ranging in size from 5 cm to 30 cm in diameter. Much of this lower segment is also covered by seaweed and small barnacles. The bottom of the exposed platform surface passes into, and presumably continues below, a sandy tidal flat, as much as 500 m in width, extending up to 1-2 m below the mid-tidal level.

## 9.0 Methodology

### 9.1 Intertidal wetting and drying: salt and de-ionized water

A series of long-term experiments are being conducted to determine the effect of tidally induced wetting and drying on shore platform development. Each of the four experimental apparatuses used in the study, which function as tidal simulators, consists of a large reservoir and three plastic basins (Fig. 1.6). Timers and pumps are used to transfer water from the reservoir into each of the basins, and then to drain it back into the reservoir at prescribed times. Rock samples were placed in the basins and elevated on a plastic screen, free from standing water once each basin was drained. The samples were exposed to the experimental conditions under conditions that simulated tidal cycles and did not accelerate the weathering processes. Water was allowed to remain within the first of the basins for eleven out of twelve hours (low tide), in the second basin for six hours (mid-tide) and in the third basin, for one hour out of twelve hours (high tide). To reduce the effects of accumulating salts from rock weathering, the pH of the water was tested weekly and, according to the degree of alkalinity, de-ionized water was replaced at least every month in the two simulators that use de-ionized water to study wetting and drying (Kanyaya and Trenhaile, 2005). The other two simulators were used to study the effect of salt weathering on rock samples, using artificial sea water (35 parts per thousand). The salinity and specific gravity of the water was tested on a weekly basis, and the water was replaced each month.

Rock cores were extracted from a variety of rock types using a diamond-studded drill bit, 1.9 cm in diameter, to produce a core 2 cm in length. Removal of the top and bottom of each core minimized the effects of pre-experimental weathering. Sandstones from Burntcoat Head in the Bay of Fundy, which were too friable to be cored, were cut into 2 cm cubes, then dried and



**Figure 1.6.** Simulators used to mimic “real time” tidal cycles: (a) fresh water tidal simulator; and (b) salt water tidal simulator.

weighed using the same procedures as for the cylindrical cores. Each core (and cube) was numbered and oven dried for 12 hours and then weighed. They were then placed in the basins and submerged in the basins for one week to obtain their maximum wet weight. After numerous tidal cycles, the rock samples were then again weighed to determine the amount of water absorbed after 11 (low tide), 6 (mid tide), and 1 hour (high tide) inundation periods. Thereafter, once the experiments had started, each sample was gently surface dried and weighed on a monthly basis. Two rock sets were used in the experiments. The first set belonged to a series of rock, composed of mainly carbonates, sandstones, igneous and metamorphic rock, collected from quarries in southern Ontario by P.P Hudec at the University of Windsor. Most of the rock samples in the Hudec collection were large enough to provide a minimum of seven cores per basin, although only five could be cored from a few of the smaller samples. A total of 534 cores from the Hudec collection were obtained, of which 324 cores were used for the fresh water tidal experiments and 210 for the salt water experiments. The second set of rock samples represented the three major rock types in the shore platforms in the study areas: argillites from Mont Louis, Québec; basalts from Scots Bay, Nova Scotia; and sandstones from Burntcoat Head, Nova Scotia. At the time of writing, more than 675 basalt, sandstone and argillite cores and cubes have been subjected to 2050 wetting and drying cycles in de-ionized water over a 34 month period. In the salt water experiments, 225 cores and cubes of basalt, sandstone and argillite have been subjected to nearly 1700 tidal cycles over a 28 month period. Another 150 basalt, 96 sandstone and 75 argillite cores have been added to the salt water experiments, and they have experienced nearly 850 tidal cycles over a 14 month period.

## 9.2 Core and cube break-down

To compare laboratory breakdown rates with platform downwearing in the field, as measured with TMEMs, the loss in weight of the cores and cubes was converted to equivalent rates of surface weathering ( $D_r$ ) ( $\text{mm yr}^{-1}$ ) using the following equation:

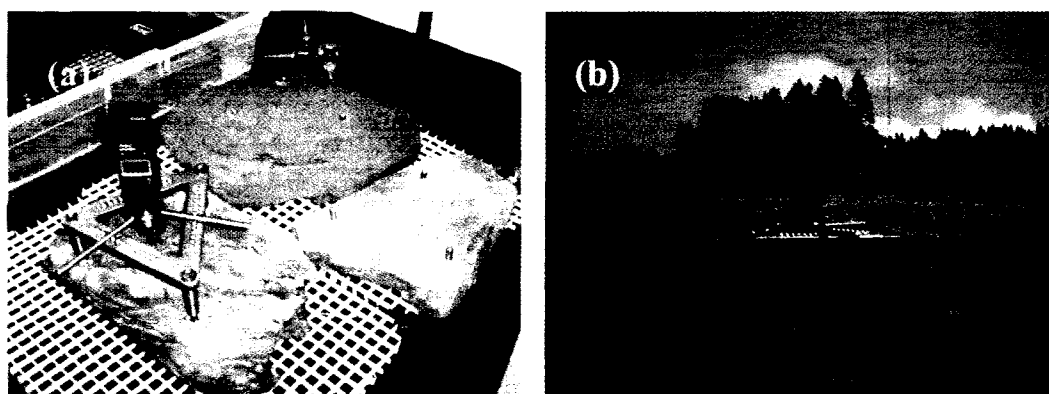
$$D_r = \frac{(W_1 - W_2)}{\rho A} \times \frac{12}{T} \times 10 \quad (1)$$

where:  $W_1$  and  $W_2$  are the initial and final surface dried wet weights (g),  $\rho$  is the rock density ( $\text{g cm}^{-3}$ ),  $A$  is the surface area of either the cylinder or cube ( $\text{cm}^2$ ), and  $T$  is the number of months that the rock sample has been subjected to wetting and drying or salt weathering.

Modes of breakdown in de-ionised and salt water vary according to the type of rock. Granular disintegration occurs in the sandstones from Burntcoat Head and the basalts from Scots Bay, but splitting along the cleavage planes is dominant in the argillites of Mont Louis. When rock fragments separated from the core or cube (usually argillites but occasionally other types of rock), the larger fragment was retained in the experiments and the smaller fragments, which were considered to be eroded segments that would have been washed away by waves, were rejected.

### 9.3 Expansion and contraction of rock surfaces

A series of short term experiments were conducted to measure the expansion and contraction of rock surfaces owing to the absorption and adsorption of water. Micro-erosion meter (MEM) stations were installed on slabs of basalt, sandstone, and argillite (approximately 35 x 25 x 10 cm in size) from the three study areas in Eastern Canada (Fig. 1.7). Each rock slab was placed within a plastic basin containing artificial sea water, and remained submerged for either eleven, six or one hour intervals, out of a twelve hour tidal cycle (representing the low, mid- and high tidal levels, respectively). Once the rocks were removed from the water, a TMEM was placed on the stations and used to measure surface elevation as the slabs dried during the remainder of the tidal cycle. To reduce potential measurement errors, the TMEM assembly remained in place for the period of exposure. MEM readings were made during the initial extraction from the solution and depending on the tidal level to be represented, every hour for eleven hours (to represent high tide), every hour for six hours (to represent mid-tide) and one hour (to represent low tide). Air temperature and humidity were also recorded on an hourly basis.

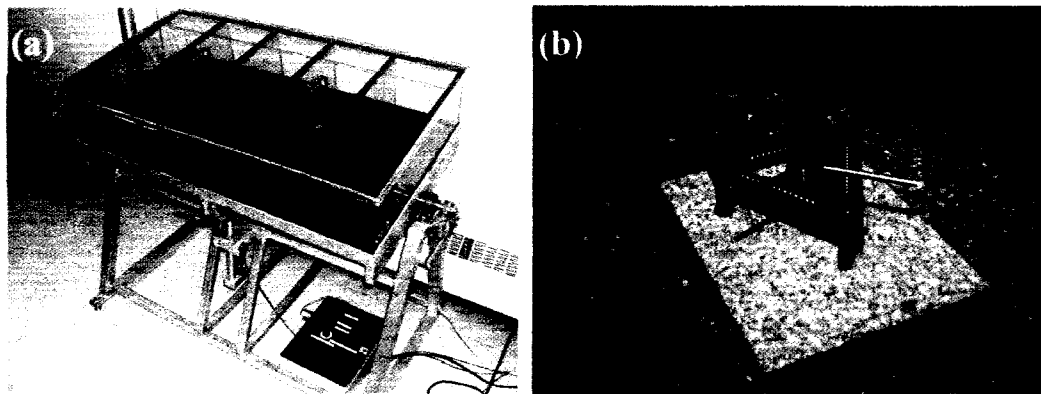


**Figure 1.7.** Measuring expansion and contraction of rock surfaces using the MEM: (a) Laboratory experiments of three samples representing rocks from Eastern Canada; and (b) MEM assembly on the Burntcoat Head platform.

Micro-erosion meter stations that are used to measure rates of intertidal downwearing in the field were also used, in the summer of 2005 and 2006, to measure surface expansion and contraction. Transversing MEMs were placed on the stations as soon as they were exposed by the falling tide, and measurements of surface elevation were made for up to 8 hours as the rock dried (Fig. 1.7). Refer to chapter three for detailed methods and results.

#### 9.4 Abrasion

Weathering and wave erosion are the primary processes contributing to the lowering of shore platforms, however, there are little quantitative data on their rates of erosion. A new apparatus was designed and constructed to study the effects of abrasion in the swash and shallow water zone of coastal regions, where current direction alternates (Fig 1.8). The apparatus consists of an oscillating top carriage, controlled by an electric motor and sensors that limit the amount of tilt, and electronic switches that allow the oscillation velocity to be varied. The carriage is composed of durable, transparent plastic, divided into five equal compartments and covered by a



**Figure 1.8.** Abrasion assembly: (a) Oscillating top carriage, comprised of 5 separate compartments; and (b) MEM station mounted on granite rock sample.

universal, removable lid. To study the abrasion of surface rock the samples need to be fairly thin, flat slabs, which requires either purchasing pre-cut rock, such as slate or granite, used primarily in home renovations, or having the rock cut professionally to specific dimensions. Rock samples are kept in place in the chambers by tight tolerances between the rock and a plastic composite; the mating pieces (rock sample and plastic composite) can be easily disassembled for rock sample replacement (Fig 1.8). Sample restraints are composed of a hard plastic composite, machined precisely to allow the surface of the rock sample to sit flush. Both the sample and restraints are placed within the compartments, and de-ionized or salt water with abrasives are



added. Various types of abrasives will be used, ranging from cobbles to fine sand. Micro-erosion meter stations will be installed in the experimental slabs and a TMEM will be used to measure rates of platform downwearing. The abrasion experiments have been designed and the equipment built during my tenure as a Masters graduate student, and I will start running them in late 2006 or early 2007. However, it will take at least one year, and probably more, to obtain meaningful results. These experiments will not, therefore, be included in my Masters graduate research.

## **10.0 Significance of the project**

There has been little research on the processes that are responsible for the development of shore platforms on rocky coasts, and most theories are based on ambiguous field evidence. This ongoing study, which began some time before I became a graduate student, represents the largest and most encompassing quantitative study of platform processes that has ever been undertaken. Large numbers of rock samples have already been subjected to hundreds of tidal cycles using de-ionized water and artificial sea water. These experiments are not only much larger than previous weathering studies in terms of the number of samples and the period of time over which they are being conducted, but they are also one of the few experiments of this type that have not accelerated the responsible mechanisms. In the field, more than 110 transverse micro-erosion meter (MEM) stations have been installed to measure downwearing rates on both sloping and horizontal platforms. This is already the largest MEM/TMEM array ever installed, and substantially more stations will be added over the next few years (to probably double the present number). In conclusion, there has been no counterpart to my study, in term of its scope and in the employment of unique laboratory equipment that will allow experimental data to be compared with, and to supplement, field data. This study will continue to provide essential data to further our understanding of the long-term development and evolution of rocky coasts in high and low tidal range environments, their response to the predicted rise in sea level, and their contribution to coastal sediment budgets.

The following two chapters consist of papers that have been submitted to international journals. Chapter 2, entitled "Shore Platform Processes In Eastern Canada" is in press with the journal *Géographie Physique et Quaternaire*. Chapter 3 is a paper entitled "Short-term rock surface expansion and contraction in the intertidal zone". This paper was submitted to the journal *Earth Surface Processes and Landforms* on July 15, 2006. The final chapter, 4, includes some material and data that have not been discussed in the papers.

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## CHAPTER 2

### Shore platform processes in eastern Canada

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#### 1.0 Introduction

There has been considerable debate over the last century on the occurrence and origin of two types of shore platform. Gently sloping platforms extend from the cliff base to below the low tidal level without any marked breaks in slope, other than those that are local expressions of structural or lithological influences. Gently sloping platforms are particularly common along the shores of the North Atlantic and in other stormy, mid-latitude environments, and they have generally been attributed to mechanical wave erosion (Everard *et al.*, 1964; Trenhaile, 1972; Sunamura, 1992). Subhorizontal shore platforms terminate abruptly seawards in low tide cliffs that are often several metres in height. Most of the literature on subhorizontal platforms has been concerned with Australasia, although these platforms are common in many warm temperate and tropical regions. Because waves operate over a range of elevations, according to tidal and weather conditions, some workers have contended that horizontal platforms are the product of weathering processes (Bartrum, 1916; Bird and Dent, 1966; Healy, 1968; Stephenson and Kirk, 2000a).

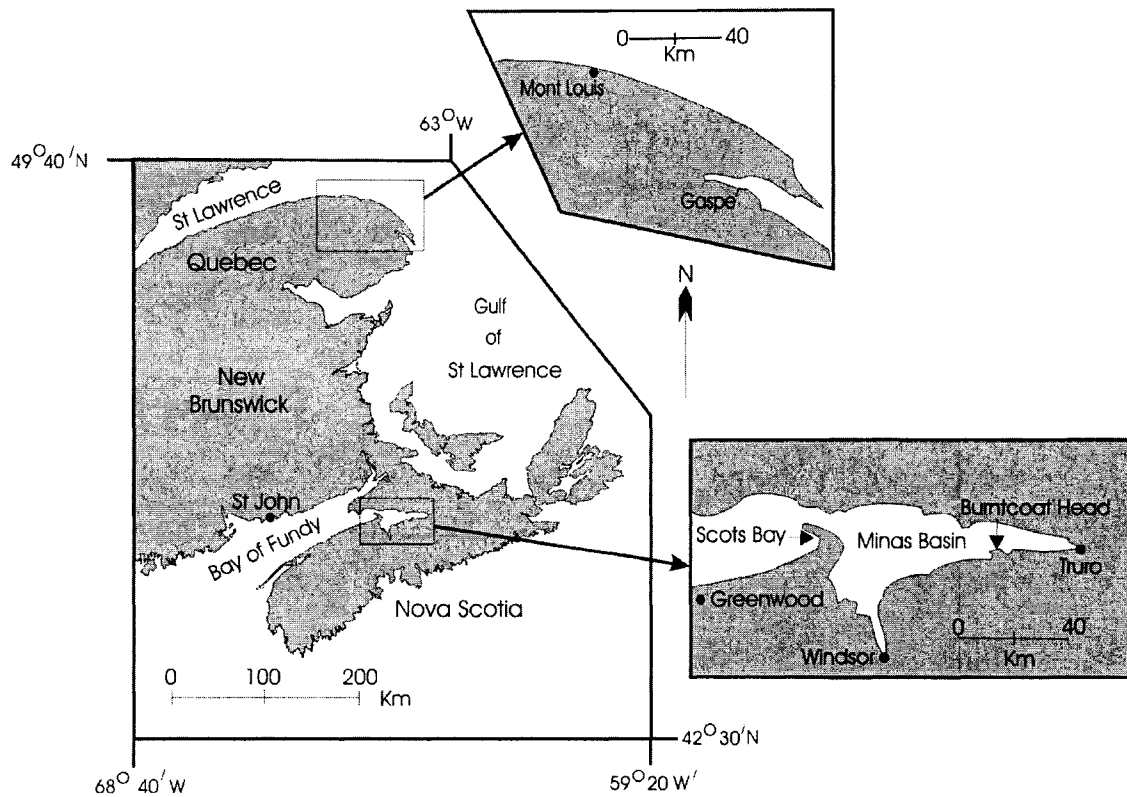
The traditional literature has largely attributed global differences in shore platform morphology to climate and wave conditions, but recent work has emphasized the importance of tidal range. Trenhaile (1987, 1999, 2000, 2001) has proposed that the tendency for mean regional platform gradient to increase with tidal range reflects, in part, the degree to which wave generated forces are concentrated within the vertical plane. Tidal range also determines the frequency of inundation and the length of the wetting and drying periods at different elevations within the intertidal zone. The range of the tide may therefore control the vertical efficacy of weathering processes and provide an additional, or alternate, explanation for the relationship between platform gradient and tidal range (Trenhaile 2003, 2004). This paper describes a series of ongoing investigations concerned with the relationship between platform processes, tidal range and shore platform morphology in eastern Canada.

#### 2.0 The study areas

The enormous variation in tidal range in eastern Canada has produced regionally dominant horizontal platforms, extending over a hundred kilometers or more in some areas, and sloping platforms in others. Studies are being conducted on sloping platforms in the Bay of



Fundy, in Triassic basalts at Scots Bay (Crosby, 1962) and in soft Middle Triassic sandstones at Burntcoat Head. A horizontal argillite platform in Middle Ordovician argillites (low grade metamorphosed shale) of the Cloridorme Formation is being studied at Mont Louis in Gaspé, Québec (Enos, 1969)(Fig. 2.1).



**Figure 2.1.** The study areas at Mont Louis in Québec and at Scots Bay and Burntcoat Head in Nova Scotia.

Tidal regimes in the study areas are semi-diurnal, although there is generally some inequality in the height of the two daily high tides at Mont Louis. The Large Tide Range (Table 2.1) is 13.5 m at Scots Bay, 16 m at Burntcoat Head (the highest range in the world), and 3 m at Mont Louis (Canadian Hydrographic Service). In the Bay of Fundy, wave direction is most frequently southwesterly, westerly and northwesterly. Almost half the deep water waves have a significant wave height of less than 0.5 m, and a peak wave period of less than 4 s. Shore-fast sea ice protects the coast from storm waves from January to April. Waves approach the Gaspé coast most frequently from the west and northwest. About 15 % of the deep water waves have a significant wave height of less than 0.5 m, and about 46 % of the peak wave periods are less than 4 s. The

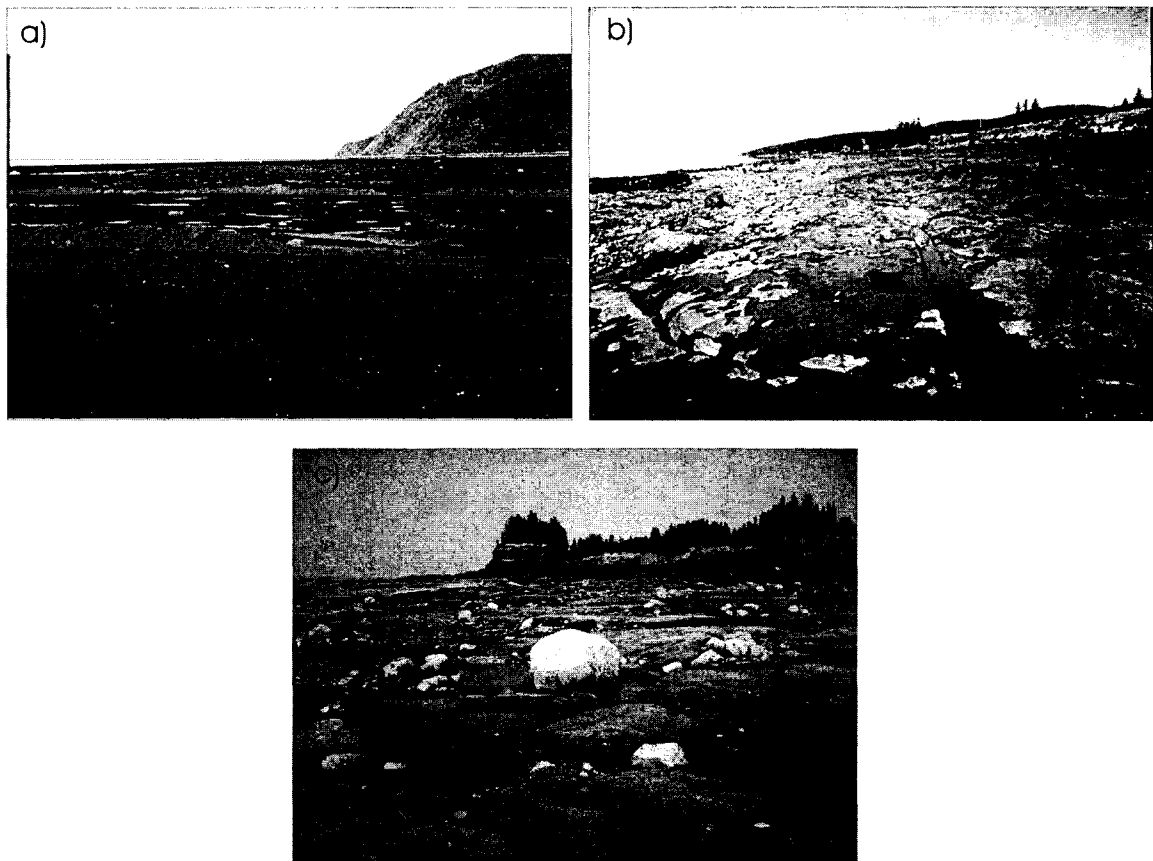
coast is protected from high waves by ice in winter, but there are less frequent periods of high waves in spring and fall (Eid, *et al.*, 1991).

The exposed portion of the Scots Bay platform, which is from 100 to 120 m in width, extends from the landward end of a sandy tidal flat, 1-2 m below the mid-tidal level, up to a grass covered rock bluff, a few metres in height, near the High High Water Large Tide level (HHWLT)(Table 2.1).

**Table 2.1.** Canadian Tidal definitions (Canadian Hydrographic Service)

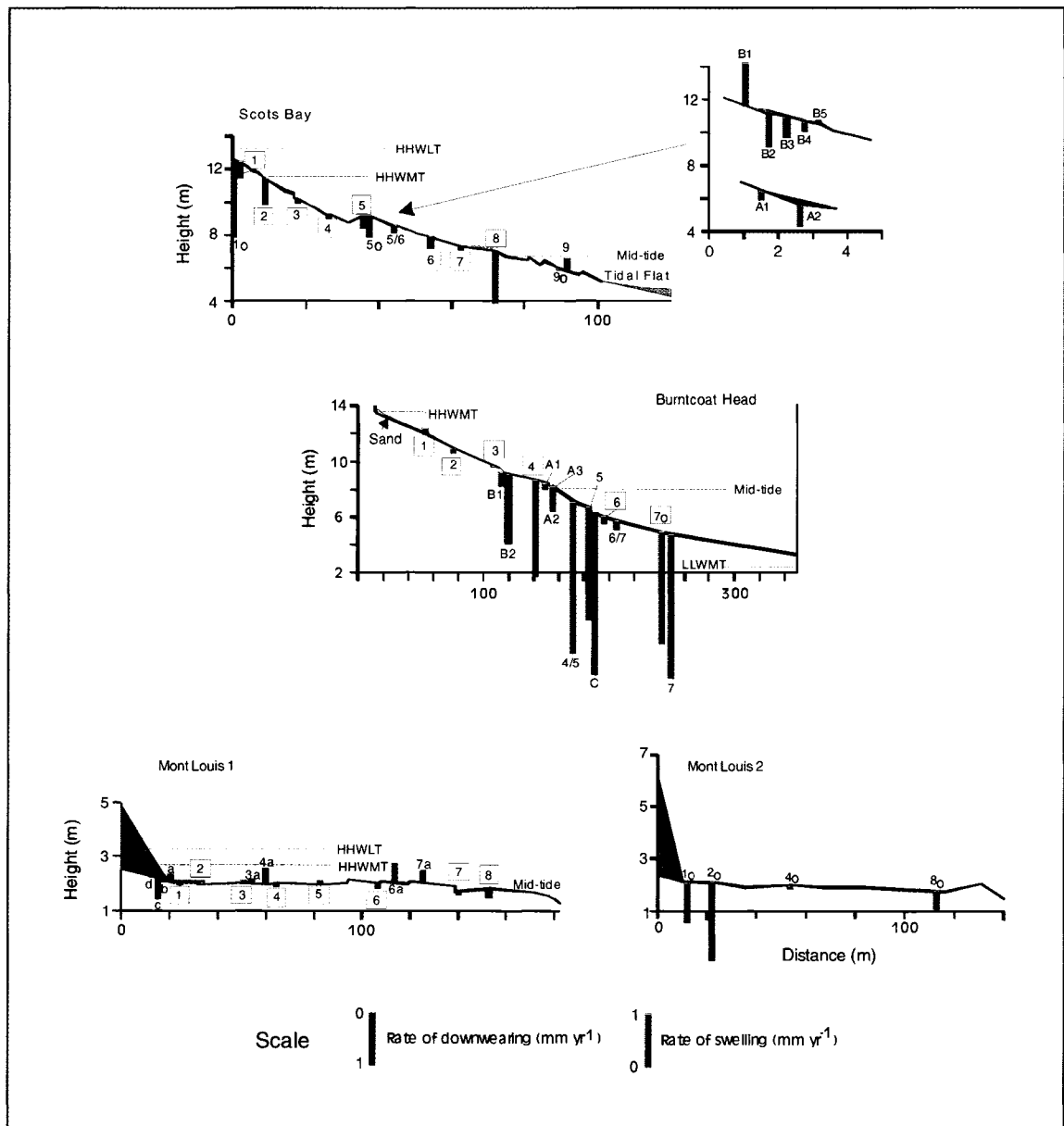
Large Tide Range	The difference between higher high water (HHWLT) and lower low water (LLWLT) at large tides
Mean Tide Range	The difference between higher high water (HHWMT) and lower low water (LLWMT) at mean tides
HHWLT	The average of the highest high waters, one from each of 19 years of predictions
LLWLT	The average of the lowest low waters, one from each of 19 years of predictions
HHWMT	The average of all the higher high waters from 19 years of predictions
LLWMT	The average of all the lower low waters from 19 years of predictions

The study area has a concave-upwards profile, with a gradient of about 7.5° in the upper part of the platform, 4.25° in the central portion and 3.5° in the lower part. The platform at Burntcoat Head is between 375 and 450 m in width. The profile in the study area is irregularly concave upwards, with a gradient of 2.5° in the upper portion and between 1° and 1.5° in the lower portion. The platform is backed by a steep, active rock cliff about 20 m high. The Mont Louis platform is horizontal, between 170 and 200 m in width, and at an elevation about 1 m above the mid-tidal level. The low cliff is a few metres in height and there is a steep coarse-grained beach at its foot; the platform terminates abruptly seawards in a low tide cliff of unknown height (Figs. 2.2 and 2.3).

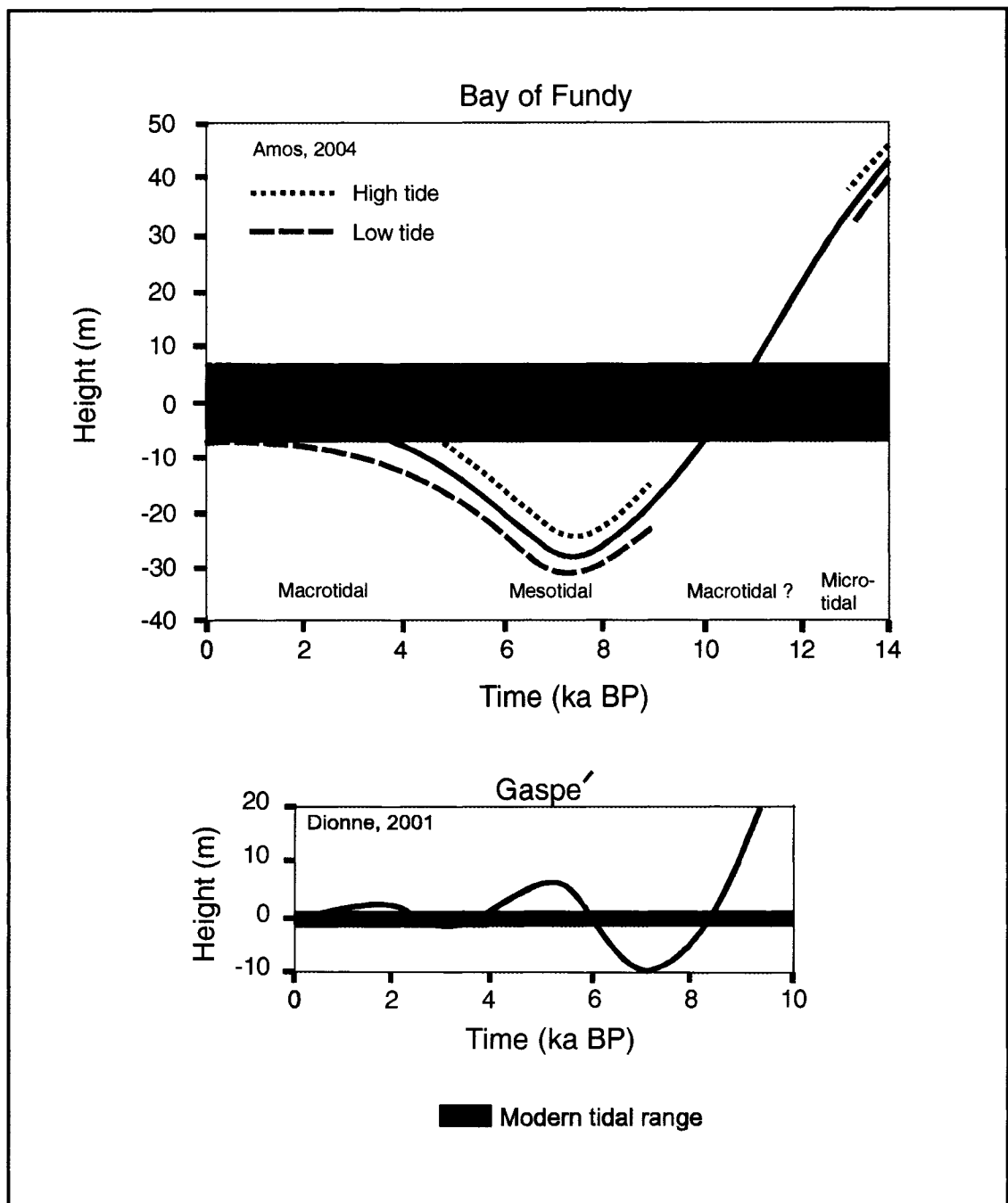


**Figure 2.2.** The three shore platforms.

The study areas in the Bay of Fundy are experiencing crustal subsidence associated with glacio-isostatic adjustment. According to Andrews (1989), relative sea level has risen by more than 6 m in the last 2,000 years, and it is presently rising at a rate of 2 m per 1,000 years. There has also been an accompanying change in tidal range in the Bay of Fundy (Amos, 2004). Dionne (2001) reasserted that glacio-isostatic uplift has generally caused relative sea level to fall over the last 10 000 years in Gaspé (Locat, 1977; Lortie and Guilbault, 1984), but he identified several marked fluctuations over the last 8,000 years, with periods of regression and transgression and sea levels higher and lower than today's (Fig. 2.4).



**Figure 2.3.** Surveyed platform profiles and TMEM downwearing data. Note that there are different vertical and horizontal scales. The TMEM station numbers in squares were those installed in May 2003.



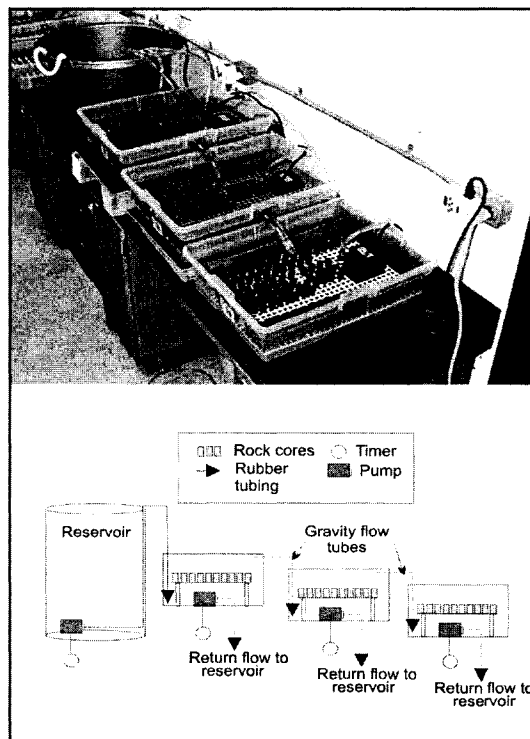
**Figure 2.4.** Changes in relative sea level on the south shore of the St Lawrence Estuary (Dionne, 2001) and in the Bay of Fundy (Amos, 2004).

### 3.0 Methodology

Experiments have been conducted on tidally induced rock weathering in the laboratory, and platform downwearing has been measured in the field.

#### 3.1 The laboratory

Tidal simulators were used to study the effect and rate of operation of tidally induced wetting and drying and salt weathering on shore platforms, with particular reference to the three study areas in eastern Canada (Fig. 2.5). On each simulator, pumps and timers circulated water from a reservoir into three basins so that rock samples were inundated for either 11, 6 or 1 h, and exposed to air for the remainder of each 12 h tidal cycle, thereby simulating conditions at the low, mid- and high tidal levels, respectively. The experiments were therefore conducted under real-time conditions with no acceleration of the erosive processes. De-ionised water was used in the wetting and drying experiments and commercial artificial sea water in the salt weathering experiments. The sea water, which is produced by Aquarium Systems Inc, has an approximate salinity of 35‰ and contains 28 ions and elements in concentrations that are similar to their occurrence in natural seawater. The temperature and relative humidity of the air were recorded almost every day.



**Figure 2.5.** A tidal simulator. Four simulators were used to measure rates of downwearing generated by wetting and drying and salt weathering.

Several slabs of rock were collected from each of the study areas and cut into samples of suitable size in the laboratory. Most samples were in the form of cylindrical cores, 1.9 cm in diameter and 2 cm in length, but because of their friability, the Burntcoat Head sandstones were cut into cubes with 2 cm long sides. The surface of the rock samples was gently dried each month for weighing, and the loss in weight, relative to core density and surface area, was used to calculate equivalent rates of surface downwearing. The experiments are continuing, but at the time of writing, 225 basalt, sandstone and argillite cores and cubes have experienced almost 1400 wetting and drying cycles in de-ionized water over a 23 month period. In the salt weathering experiments, 75 cores and cubes have experienced more than 1000 salt weathering cycles over a 17 month period, and 150 basalt, 96 sandstone and 75 argillite cores and cubes have experienced almost 200 cycles over a three month period. Kanyaya and Trenhaile (2005) found that almost no downwearing took place in most of the cores and cubes in the first few months of the experiments with de-ionized water. Therefore, although the experiments with de-ionized water have been conducted for 6 months longer than those with artificial sea water, we only used data from the first 17 months of each type of experiment in order to compare the effects of wetting and drying and salt weathering.

### **3.2 The field**

A micro-erosion meter (MEM) consists of an engineer's dial gauge that measures the downward extension of a needle-like probe. The gauge and probe sit on a low, triangular frame that, in use, is positioned on three metal bolts (a MEM station) permanently embedded in the rock surface (High and Hanna, 1970; Robinson, 1976). The instrument allows precise measurements to be made of slow rock downwearing (erosion in the vertical plane) and several workers have used it in the supra- and intertidal zones of rocky coasts (Kirk, 1977; Robinson, 1977; Gill and Lang, 1983; Mottershead, 1989; Stephenson and Kirk, 1998; Foote *et al.*, 2001; Andrade *et al.*, 2002). Unlike the MEM, which allows only three measurements to be made at each station, a traversing micro-erosion meter (TMEM) permits numerous measurements to be made within the triangular frame of the instrument (Trudgill *et al.*, 1981; Stephenson, 1997).

Traversing micro-erosion meter stations were installed along surveyed, shore-normal profiles at Scots Bay, Burntcoat Head and Mont Louis in August 2002. Although many of the bolts soon rusted or broke, a number did remain in good condition and downwearing data were obtained in May 2003 from 8 stations along two profiles at Mont Louis, 3 stations along a profile at Scots Bay and 4 stations along a profile at Burntcoat Head. The original TMEM stations were then abandoned and replaced by 22 new stations, using a higher-grade stainless steel bolt of a

more rugged design. These new stations were installed in the three study areas in May 2003, and measurements were made in June 2004. An additional 23 stations were installed in May 2003, and measurements were made at all existing sites in July 2005 (Fig. 2.3). Data from another 30 stations, which were installed in July 2005, will not be available until the summer of 2006. Mean annual downwearing rates ( $\text{mm yr}^{-1}$ ) are reported in this paper from 56 TMEM stations, covering a period from 1 to 3 years. These rates are the means of the seven readings that were made at different points at each TMEM station, calculated from the time of installation to the most recent period of measurement.

The TMEM stations in eastern Canada occupy three types of site: extensive areas of bare rock; the edges of pockets of sand, gravel and other potentially abrasive material; and rock surfaces beneath various thicknesses of beach material. The stations were generally located at roughly equal intervals along surveyed, shore normal profiles; although it was sometimes necessary to install sites off-profile in order to measure the abrasive effect of localized beach deposits. Because of the distance to the study areas and the occurrence of thick sea ice in winter, it has only been possible so far to take measurements each summer.

Several workers have used compressive strength, or the related Schmidt Rock Test Hammer rebound value, to represent rock resistance to coastal processes, and to measure the spatially variable effect of weathering on the strength of the rock (Tsujimoto, 1987; Sunamura, 1992; Haslett and Curr, 1998; Trenhaile *et al.*, 1998, 1999; Stephenson and Kirk, 2000a, 2000b; Andrade *et al.*, 2002; Dickson *et al.*, 2004). In eastern Canada, 30 measurements were made at each TMEM station with an N-type Rock Test Hammer, and the mean of these values was used to represent rock strength at each site.

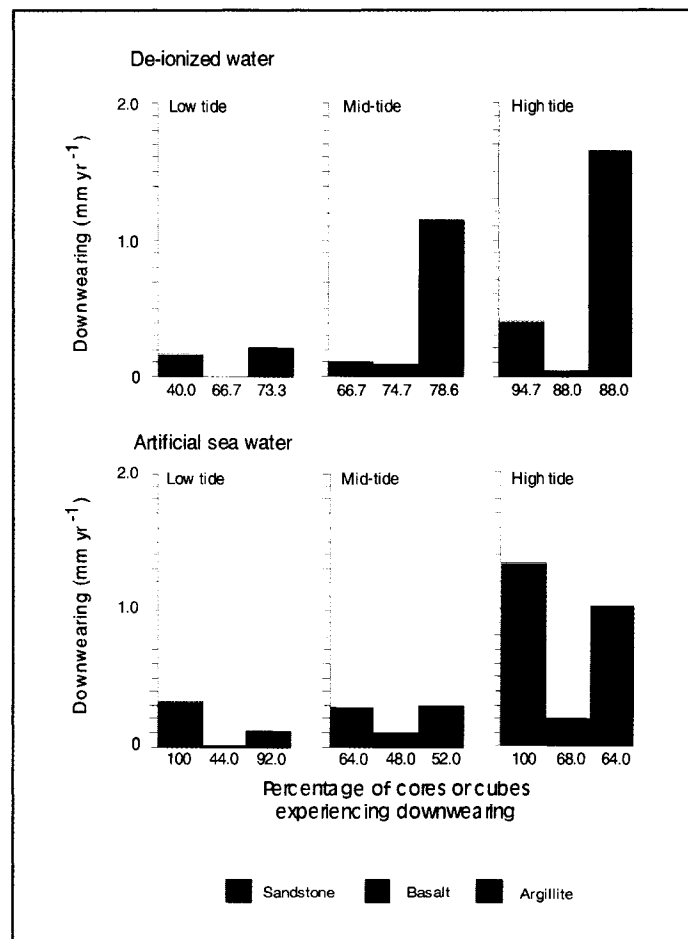
Waves have been measured over complete tidal cycles at Scots Bay and Mont Louis, using graduated steel poles and video-recorders. Significant and maximum wave height and period were determined at each tidal stage, and nearshore wave equations were used to estimate breaker type, height and period, surf zone width and the dynamic force exerted by the broken waves under more extreme storm conditions (Trenhaile and Kanyaya, in press). Waves were not recorded at Burntcoat Head because the high cliff prevents access to, or escape from, the back of the platform during high tide.

#### **4.0 Results**

The laboratory experiments showed considerable variation in the rate of breakdown by wetting and drying in de-ionized water between cores and cubes from different rock slabs, and between cores and cubes from the same slab. Nevertheless, the results demonstrated that the



argillites are much more susceptible to wetting and drying than the sandstones or basalts (Fig. 2.6). Mean rates of argillite downwearing increased with elevation in the intertidal zone, and there was a commensurate increase in the proportion of the cores that experienced breakdown. Nevertheless, downwearing rates for individual cores ranged from 0 to more than 3.2 mm yr<sup>-1</sup>. Rates of sandstone cube downwearing, which ranged from 0 up to an extreme of 0.58 mm yr<sup>-1</sup>, were much lower than in the argillites. Sandstone downwearing was fastest at the high tidal level. Although a higher proportion of the cubes experienced breakdown at the mid- than at the low tidal level, the mean rate of downwearing was higher at the low than at the mid-tidal level. A fairly high proportion of the basalt cores experienced some breakdown, especially at the high tidal level, but downwearing rates, ranging from 0 up 0.58 mm yr<sup>-1</sup>, were the lowest of the three types of rock. Mean rates were less than 0.1 mm yr<sup>-1</sup>, and were highest at the mid-tidal level.



**Figure 2.6.** Downwearing rates measured over 17 months in de-ionized and artificial sea water. Negative values, caused by increased water retention, and possibly associated with surface swelling, were omitted from the analysis. The numbers listed beneath each column represent the percentage of each rock type sample, at each simulated tidal level, that experienced downwearing.

The breakdown of rock cores and cubes in artificial sea water is accomplished by salt weathering and alternate wetting and drying, and probably also by some chemical weathering. Nevertheless, wetting and drying in de-ionized water caused more rapid breakdown of the argillites than the combined effect of these three mechanisms in artificial sea water (Fig. 2.6). The results therefore suggest that the presence of salts in some way inhibits the effect of wetting and drying in this type of rock, although the experiments need to be run for a longer period to confirm that this unexpected relationship is real. Rates of argillite breakdown in artificial sea water ranged from 0 to almost  $2.3 \text{ mm yr}^{-1}$ . As in the experiments with de-ionized water, breakdown was fastest at the high tidal level and slowest at the low tidal level, although there was a much greater frequency of core breakdown at the low than at the mid- or high tidal levels. The sandstone cores were the most susceptible to downwearing in artificial sea water, and rates, and generally frequencies, of breakdown were significantly higher than in de-ionized water. Downwearing rates ranged from 0 to  $2.65 \text{ mm yr}^{-1}$ , and were consistently high at the high tidal level, where all 25 cubes experienced some breakdown. Rates of basalt downwearing were also higher in artificial sea water than in de-ionized water, although breakdown was less frequent. Rates of downwearing ranged from 0 to  $0.73 \text{ mm yr}^{-1}$  and increased with elevation within the intertidal zone.

The TMEM data often show considerable variation in downwearing rates from one year to the next, and sometimes between adjacent sites that are on the same rock stratum and at essentially the same elevation. Therefore, although the number of TMEM sites and the period over which the data have been collected surpass that of most previously published studies of this type, the downwearing data should be treated with some caution until measurements have been made for a much longer period and from more TMEM stations. The highest downwearing rates were recorded at several TMEM stations near the mid-tidal level in the sandstones at Burntcoat Head (Fig. 2.3). There was no significant correlation between rock hardness, as measured with the Schmidt Rock Test Hammer, and rates of downwearing in the area extending from TMEM stations 3 to 7, although abrasion may account for fairly rapid erosion at: station B2, which is under about 5-7 cm of sand; station 4/5, which lies a short distance landwards of a pocket of sand; and station C (downwearing  $3 \text{ mm yr}^{-1}$ ) which is in a shallow pothole and under 1 - 2 cm of sand. The absence of abrasive material in the lower part of the platform eliminates the potential effect of this factor at stations 7<sub>o</sub> and 7 (downwearing  $2.09$  and  $2.66 \text{ mm yr}^{-1}$ , respectively), and although there is sand in the area around stations 4 and 4/5 (downwearing  $1.76$  and  $2.83 \text{ mm yr}^{-1}$ , respectively), their local elevation about 0.5 m above the general platform surface suggests that abrasion is also probably ineffective in these areas. Low downwearing rates at stations 1, 2 and 3 in the upper portion of the profile, where the laboratory data suggest that wetting and drying and

salt weathering are most effective, may be attributed to the occurrence of a thin, protective veneer of mud, which is absent at lower elevations.

Downwearing rates were much lower in the basalts of Scots Bay than in the sandstones of Burntcoat Head. Rates ranged from a high of  $1.42 \text{ mm yr}^{-1}$  at station 1<sub>o</sub>, to lows of  $0.06$  and  $0.07 \text{ mm yr}^{-1}$  at stations 4 and 7, respectively. There was only a very low correlation between rock hardness and downwearing rates at Scots Bay. Rates were consistently low below the High Water mean tidal level (HHWMT)(Table I), with the exception of station 8, which is on a ridge that stands about 0.5 m above a boulder-covered section of the platform. Although the topography suggests that the rock at station 8 is more resistant than its surroundings, this conclusion is belied by a fairly high rate of downwearing, and a Rock Hammer Rebound Value of 26, compared with 31 at stations 6 and 7.

TMEM data are also available at Scots Bay for 7 stations that were installed about 200 m west of the main profile in the summer of 2004. Stations B1 to B5 are situated along a short, shore-normal line, about 2 m long, in the mid-tidal zone. Stations A1 and A2, which are also shore-normal and mid-tidal, are about 2 m apart and situated approximately 15 m to the east of the B1-B5 stations. Stations B2 to B4 and A2 are beneath several centimetres of basaltic gravel ranging up to about 1 cm in diameter. In each case, downwearing over the last year has been greater at stations under the abrasive material than at exposed stations located on the same rock surface and at similar elevations (Fig. 2.3). Although there is generally little loose material on the platform at Scots Bay, the data therefore suggest that abrasion is an effective erosional process on the basalt where abrasives are available.

Rates of downwearing at Mont Louis ranged between  $0.01$  to  $1.57 \text{ mm yr}^{-1}$ , although they were generally quite low, and there was only a very weak correlation with rock hardness. A few workers have reported negative MEM values caused by rock surface elevation or swelling at some stations. Swelling events, ranging in some extreme cases up to several millimetres, can persist for a few months up to a couple of years. They have been attributed to salt crystallization, although wetting and drying is thought to play a less important role (Kirk, 1977; Mottershead, 1989; Stephenson and Kirk, 2001). Only a few TMEM stations on the sandstone and basalt platforms in the Bay of Fundy recorded mean rates of platform swelling (rock surface elevation between measurement intervals), but they were common on the argillite platform at Mont Louis (Fig. 2.3). This may be partly the result of the uneven yet overall horizontal nature of the platform surface at Mont Louis, which allows shallow, intertidal pools to persist on the platform for long periods. Recent work, however, suggests that negative TMEM values are largely a

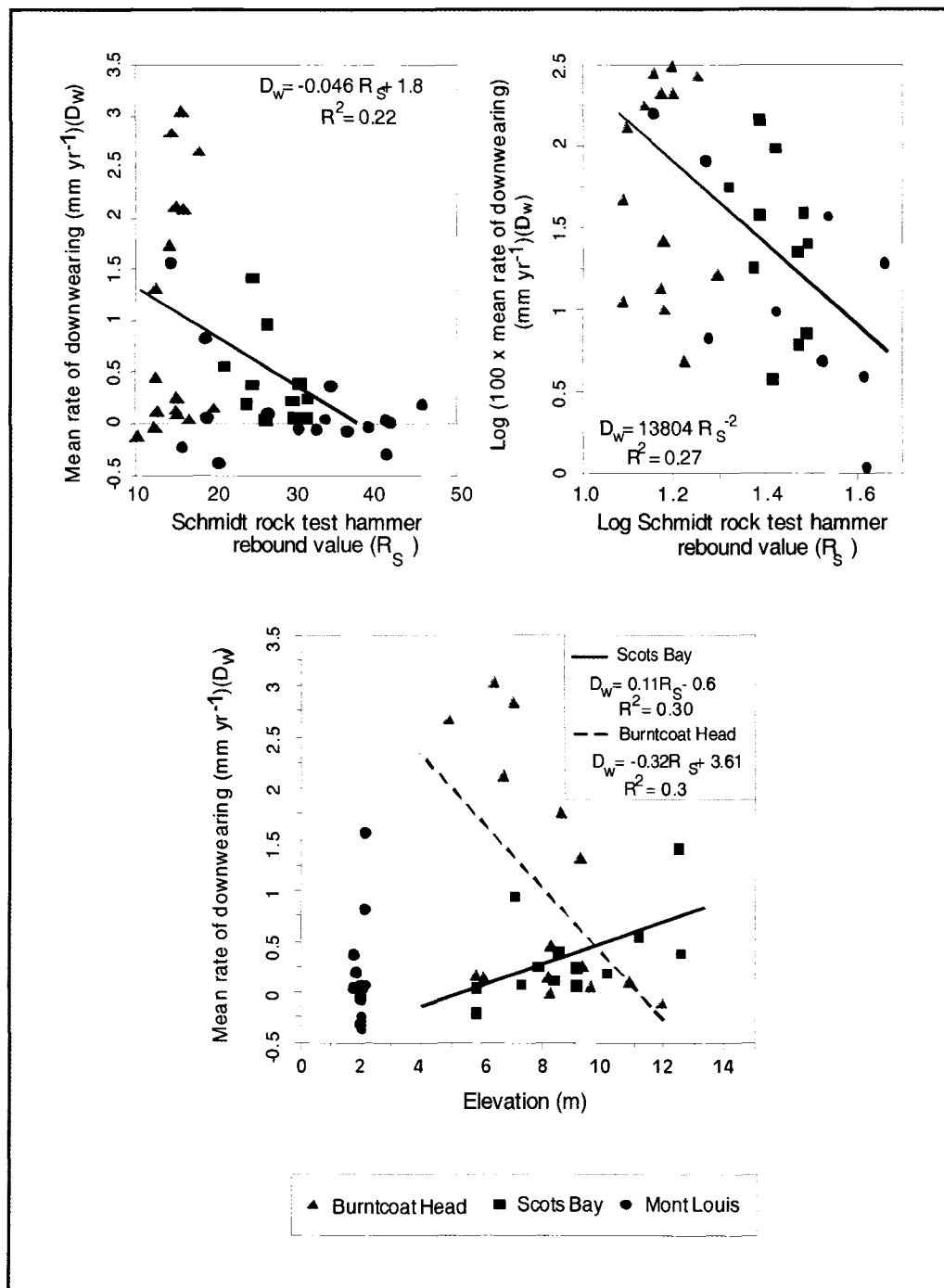
reflection of the swelling capacities of the argillite's dominant chlorite and illite clay minerals (Trenhaile, in press).

To study the effect of abrasion, four TMEM stations (a to d) were installed at the rear of the Mont Louis platform in summer 2004. The stations are on the same rock outcrop, roughly aligned along a shore-normal profile, about 3 m long. Station a, which is furthest seawards, and station b are on bare rock surfaces, a metre or so from the foot of the steep, predominantly shale, beach. Station c is under about 8 to 12 cm of sediment and station d, which is furthest landwards, is under about 25-35 cm of material: these sites have to be excavated from beneath the sediment in order to make the TMEM measurements. Over the last year there has been slight surface expansion at station a, slight downwearing at station b, much more downwearing at station c and expansion at station d (Fig. 2.3). It is tempting to suggest that fairly fast downwearing at station c is the result of abrasion under a thin deposit that can be mobilized during storms, whereas the lack of erosion at station d reflects the occurrence of a thicker, more immobile deposit (Robinson, 1977). It is questionable, however, whether shale fragments are effective abrasives, and as the rock surface is kept very wet under the beach, it may be that patterns of downwearing and swelling are, instead, the result of water absorption, salt crystallization, or chemical processes; laboratory experiments are being designed to investigate these possibilities.

There was little relationship between rates of downwearing and rock hardness in each study area, and rock strength accounted for only about 1/4 of the variation in downwearing when the data for all three sites were combined (Fig. 2.7). Surface elevation determines how often an area is covered by the tide, and the resulting duration of the periods of exposure and inundation. There was no relationship between TMEM station elevation and downwearing rates for the combined data for the three areas, however, although there were significant, albeit fairly weak, relationships between these variables for the basalts of Scots Bay and the sandstones of Burntcoat Head (Fig. 2.7).

Basaltic rates of downwearing, measured in the field and in the laboratory (in artificial sea water), are fairly consistent, and rates of breakdown in the field, as predicted in the laboratory, are higher at the high than at the mid-tidal level (the lower portion of the platform at Scots Bay is beneath a tidal flat). Sandstone downwearing rates at Burntcoat Head are also fairly consistent with the range of values obtained in the laboratory experiments. The highest downwearing rates are around the mid- rather than the high tidal level, however, which is contrary to the experimental results: TMEM data from the Lower Low Water Mean Tide level (LLWMT)(Table I) will not be available until next summer. The platform at Mont Louis is horizontal and although the surface is uneven in places, there is little variation in the elevation of

the TMEM stations. Rates of downwearing in the field were quite low and consistent with those recorded in the laboratory at the mid-tidal level.



**Figure 2.7.** Relationships between rock strength, TMEM station elevation and rates of downwearing in the three study areas.

## 5.0 Discussion

The platform at Mont Louis is dry or under shallow water for most of the tidal cycle, and waves break on, or over, the low tide cliff. Deeper water allows fairly large waves to cross the platform during high spring tides, but the cliff base is protected by a coarse-grained beach and only a few upstanding ridges of resistant rock are exposed to wave action at this elevation (Trenhaile and Kanyaya, in press). Nevertheless, there is effective wave erosion at the base of vertical and undercut cliffs all along the Gaspé coast where there are no protective beaches. Given the general absence of abrasive material and the lack of smooth abraded surfaces, this implies that the Mont Louis platform was initially cut by waves near the high tidal level and subsequently lowered by weathering to its present elevation. Although weathering dominates on the platform today, backwearing by waves and frost will gradually assume greater importance. This is, in part, because argillite downwearing rates decline with decreasing platform elevation, and also because weathering by wetting and drying and salt crystallization cannot operate today on the floors of the large, shallow pools that cover much of the platform surface. Renewed downwearing of the weak argillites in these water-filled depressions must therefore wait until the pools are drained, which requires removal of the more resistant, intervening ridges by wave and frost quarrying.

Large joint blocks have been undercut and dislodged along the front of seaward facing scarps at Scots Bay. Backwearing by waves, probably assisted by frost, therefore operates, along with downwearing by weathering, on this platform. The laboratory experiments, which are supported, in part, by the TMEM data, suggest that downwearing rates on the basalt surface are fastest at the high tidal level. The upper portion of the platform, however, also experiences the strongest wave forces and, presumably, the most rapid rates of scarp erosion and backwearing (Trenhaile and Kanyaya, in press).

The laboratory experiments suggest that rates of platform downwearing on the sandstones of Burntcoat Head are much greater at the high than at the low tidal level. The TMEM data show that the fastest rates of downwearing by weathering are actually close to the mid-tidal level, however, in the vertical zone that experiences not only the greatest number of tidal wetting and drying cycles each year, but also the greatest frequency of wave action (Trenhaile, 2003; Trenhaile and Kanyaya, in press): lowering by wave abrasion is also important in shallow potholes and where there is a thin layer of sand. Several workers have proposed that weathering rather than wave erosion is responsible for platform downwearing, which has been found to be faster in summer, when air temperatures are higher and wave action is generally weaker, than in winter (Robinson, 1977; Mottershead, 1989; Stephenson and Kirk, 1998). Turbulent waves may

facilitate removal of the loosened, weathered sand grains at Burntcoat Head, however, which would account for the mid-tidal downwearing maximum in the zone of most frequent wave action, and for the discrepancy between sandstone downwearing rates measured in the laboratory and in the field.

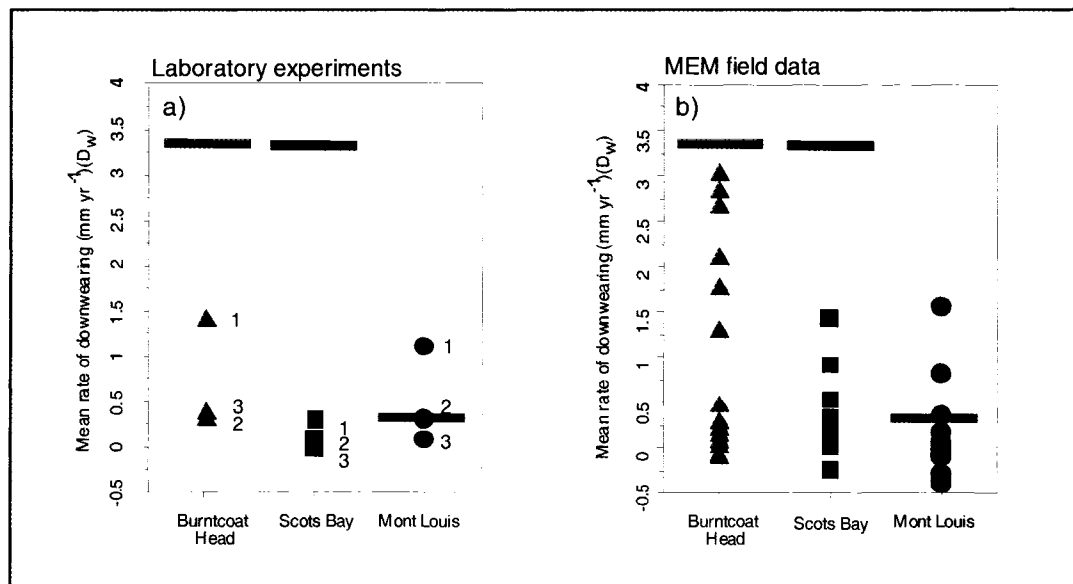
Micro-erosion meters allow precise measurement of the rate of surface downwearing on shore platforms. They cannot record the effects of wave quarrying or frost riving of large rock fragments and joint blocks, however, and therefore cannot be used to compare the relative importance of wave and weathering processes. Trenhaile and Kanyaya (in press) have demonstrated that wave generated forces on the coast of Gaspé and in the Bay of Fundy are strong enough to quarry large joint blocks, but because of the episodic and localised nature of block quarrying it has not been possible to quantify its absolute or relative importance in the development of shore platforms. Nevertheless, although one cannot measure directly the contribution of wave and frost quarrying (backwearing), it may be possible to estimate its historical importance in eastern Canada, and potentially elsewhere, by simply subtracting the amount of erosion accomplished by downwearing from the total amount of erosion required to produce a platform.

Most shore platforms are produced by the erosion and retreat of sea cliffs. Cliffs are generally undercut by waves and other marine processes, forming a surface that is initially at the height of the cliff-platform junction (the cliff foot or base). This surface is then gradually reduced in elevation by waves, weathering and biological agencies. The height of the cliff-platform junction, relative to platform elevation, is therefore an indication of the amount of lowering that has taken place at various points within the intertidal zone. The elevation of the cliff-platform junction varies according to rock strength and wave energy, but it is usually close to the high tidal level (Wright, 1970; Trenhaile, 1978, 1987). Although the junction is hidden under a coarse-grained beach at Mont Louis, it is generally close to the HHWMT level along adjacent areas of this coast (Trenhaile, 1978). The base of the low cliff at Scots Bay is between the HHWMT and HHWLT levels, and the foot of the undercut, eroding cliff at Burntcoat Head is close to the HHWMT level.

In Gaspé, Holocene sea level has been within or very close to the present tidal range for the last 4000 years, and for only a couple of brief periods previously (Dionne, 2001). To have produced the Mont Louis platform over this time would have required a mean backwearing rate of about  $4.5 \text{ cm yr}^{-1}$  (given a platform width of 180 m), and a downwearing rate of about  $0.30 \text{ mm yr}^{-1}$  (to lower the platform 1.20 m from the HHWMT level to its present elevation). Waves and frost were probably quite capable of attaining cliff backwearing rates of this magnitude in

friable argillites, particularly when the platform was much narrower during the earlier stages of development, and the required mean downwearing rate is compatible with measured rates in the field and these obtained in the laboratory (Fig. 2.8).

In the Bay of Fundy, Holocene mean sea level has also been within the present tidal range for about the last 4000 years (Amos, 2004). Platform formation during the Holocene would therefore have required cliff foot backwearing rates of about 10 to 12.5 cm yr<sup>-1</sup> at Burntcoat Head (width 400 to 500 m) and, assuming that the platform continues below the tidal flat to the low tidal level with approximately the same gradient, about 3.8 cm yr<sup>-1</sup> at Scots Bay (estimated width 150 m). For downwearing to have been entirely responsible for lowering platform surfaces in the Bay of Fundy from the elevation of the cliff foot, it would have had to operate at a mean rate of about 3.3 mm yr<sup>-1</sup> at the seaward edge of the Scots Bay platform. The corresponding downwearing rate for the seaward edge of the platform at Burntcoat Head would be about 3.4 mm yr<sup>-1</sup>. Measured rates of downwearing, in the field and the laboratory, are therefore too low to account for the amount of lowering that has occurred at the low tidal level in the Bay of Fundy. Assuming, given the lack of evidence to the contrary, that these platforms are entirely postglacial, other agents, particularly backwearing by waves and frost quarrying, must have been responsible for approximately one-half to two-thirds of the erosion that has occurred at Burntcoat Head, and from two-thirds (based on TMEM downwearing data) to over nine-tenths (based on laboratory downwearing data) of the erosion at Scots Bay (Fig. 2.8).



**Figure 2.8.** a) Mean rates of laboratory downwearing by weathering in artificial sea water at the high, mid- and low tidal levels (numbered 1, 2 and 3, respectively). b) Platform downwearing measured in the field with a TMEM. The shaded, horizontal bars represent the mean rates of downwearing, by all processes, that would have been required to reduce the seaward edge of the platforms in the study areas from the high to the low tidal level (LLWLT)(Table I) over the last 4000 years.



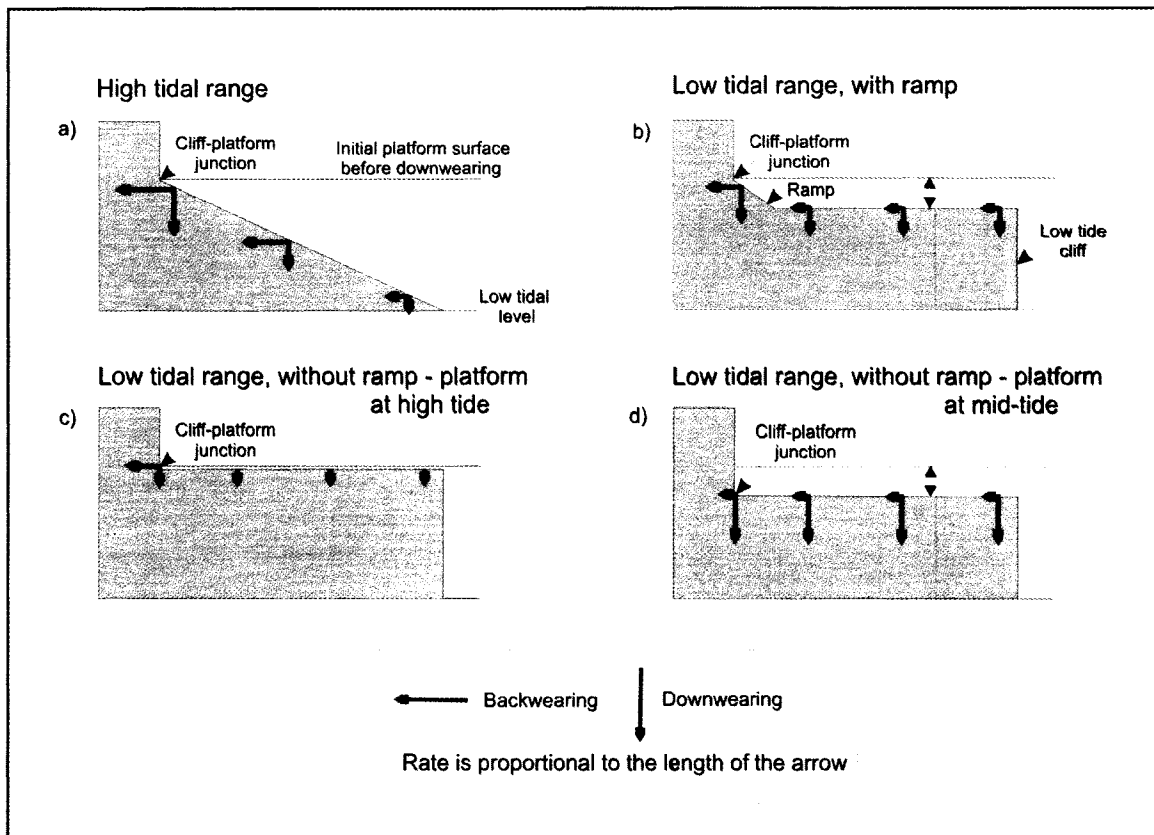
### 5.1 A shore platform model

There appear to be fundamental differences in the efficacy of the processes operating on the horizontal and sloping shore platforms of eastern Canada, and consequently in the mode of platform development:

- a) Mechanical wave erosion can operate at a variety of elevations on the sloping platforms in the macrotidal Bay of Fundy, although it is generally most effective in the middle to upper portions of the intertidal zone (Trenhaile and Kanyaya, in press). The experimental data suggest that downwearing by weathering is normally most effective in the higher parts of the intertidal zone. In the sandstones of Burntcoat Head and in other weak rocks that granularly disintegrate, however, waves may accelerate the process by removing loosened, weathered grains. In such cases, the fastest rates of downwearing may be around the mid-tidal level, which experiences most frequent wave action (Fig. 2.9a).
- b) Waves break on or over the low tide cliff, the abrupt seaward terminus of the horizontal shore platforms that characterize the low mesotidal coast of Gaspé. Several subtypes may be identified which vary according to the relative importance of the backwearing and downwearing agents which, in turn, reflect the mechanical strength of the rock, its susceptibility to wetting and drying and other weathering processes, the tidal range and the strength of the waves. Waves become increasingly less effective erosional agents at the cliff foot as horizontal platforms widen. Weathering can lower the platform surface and increase the depth of the water during high tidal periods, however, thereby allowing the waves to either retain or regain their ability to erode the cliff foot.

Wave erosion at the cliff foot and downwearing by weathering on the platform can produce a more steeply sloping ramp at the foot of the cliff (Fig. 2.9b) although, as at Mont Louis, the ramp may be concealed under, or replaced by, a beach. Rapid cliff erosion and slow downwearing may produce a horizontal platform near the high tidal level (Fig. 2.9c). Shallow water over the platform would eventually prevent effective wave action, however, and this condition is therefore likely to exist only in the early stages of platform development when the

platform is still very narrow. It is also possible that cliff erosion could essentially cease as a platform became very wide. More rapid downwearing in the upper portion of the intertidal zone would remove any ramp that had previously formed (Fig. 2.9d). Assuming that mechanical wave erosion, rather than frost, shore ice, wetting and drying or salt weathering, is responsible for cliff backwearing, this is also likely to be a temporary condition, as deeper water over the platform, as it is reduced by downwearing, would gradually restore the ability of the waves to attack and erode the cliff foot.



**Figure 2.9.** A generalized process model for sloping, macrotidal and horizontal mesotidal shore platforms in eastern Canada. Rates of backwearing relative to downwearing will vary from place to place according to such factors as wave regime, tidal range, climate and geology.

## 6.0 Conclusions

The absolute and relative efficacy of the wide variety of processes that operate on shore platforms vary temporally and spatially according to such factors as wave regime, tidal range, air temperature and other climatic factors, rock structure, hardness, mineralogy and other geological characteristics, and the elevation, gradient and other aspects of platform morphology. Although a particular process suite may be dominant at a particular time or in a particular place on a platform

surface, the traditional, simplistic assumption that horizontal platforms are formed by weathering and sloping platforms by wave action must be rejected.

Although the various components of this research need to be continued for some time, preliminary field and laboratory data suggest that:

- a) Despite the occurrence of some loose quarried blocks along the scarps of ridges of more resistant rock, wave action is presently largely ineffective on the horizontal, mesotidal platform at Mont Louis. Although the argillaceous platform may have been cut initially by waves at the high tidal level, it is being lowered by weathering today.
- b) The sloping, macrotidal platform at Scots Bay is the product of wave and weathering process. Although backwearing by mechanical wave erosion and frost has probably been more important than downwearing by weathering in the past, backwearing is limited today to the undercutting of a few basaltic scarps and, in the absence of much abrasive material, slow downwearing by weathering dominates over most of the platform surface.
- c) The friable sandstones in the macrotidal, sloping platform at Burntcoat Head are much weaker than the basalts of Scots Bay. Therefore wave action probably plays an important role in removing loosened weathered material, thereby contributing to platform downwearing. Abrasion is significant where there are pockets of loose sand. Although scarps are generally less prominent here than at Scots Bay, the data suggest that backwearing by wave quarrying and probably by frost has been at least as important as downwearing on this platform in the Holocene.

In summary, the results of this study suggest that waves and weathering are both important on sloping shore platforms, which is contrary to recent statements by Stephenson and Kirk (2000b) regarding the inability of waves to erode coastal rocks. Conversely, the results generally support Stephenson and Kirk's (2000a) conclusion that weathering may be dominant today on some horizontal platforms, although the Mont Louis platform may have been cut originally by waves.

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## CHAPTER 3

### Short-term rock surface expansion and contraction in the intertidal zone

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#### 1.0 Introduction

Although shore platforms have been studied for more than 100 years, theories of platform development and explanations for differences in platform morphology have, until recently, been based largely on potentially ambiguous field evidence. A growing number of workers are now providing the information needed to make more reliable interpretations based on rates of erosion and identification of the processes operating on shore platforms in a variety of morphogenic environments. Much of the erosional data have been obtained through the use of micro-erosion meters (MEMs) or transverse MEMs (TMEMs) to measure slow rates of platform downwearing (Kirk, 1977; Robinson, 1977; Gill and Lang, 1983; Mottershead, 1989; Stephenson and Kirk, 1998, 2000; Foote *et al.*, 2001; Andrade *et al.*, 2002, Trenhaile and Kanyaya, 2004; Trenhaile *et al.*, in press). These instruments do not measure the effects of block quarrying by waves or frost action (Trenhaile and Kanyaya, in press), however, and although they can provide important clues to the processes responsible for surface downwearing, the interpretations are often inconclusive and open to debate.

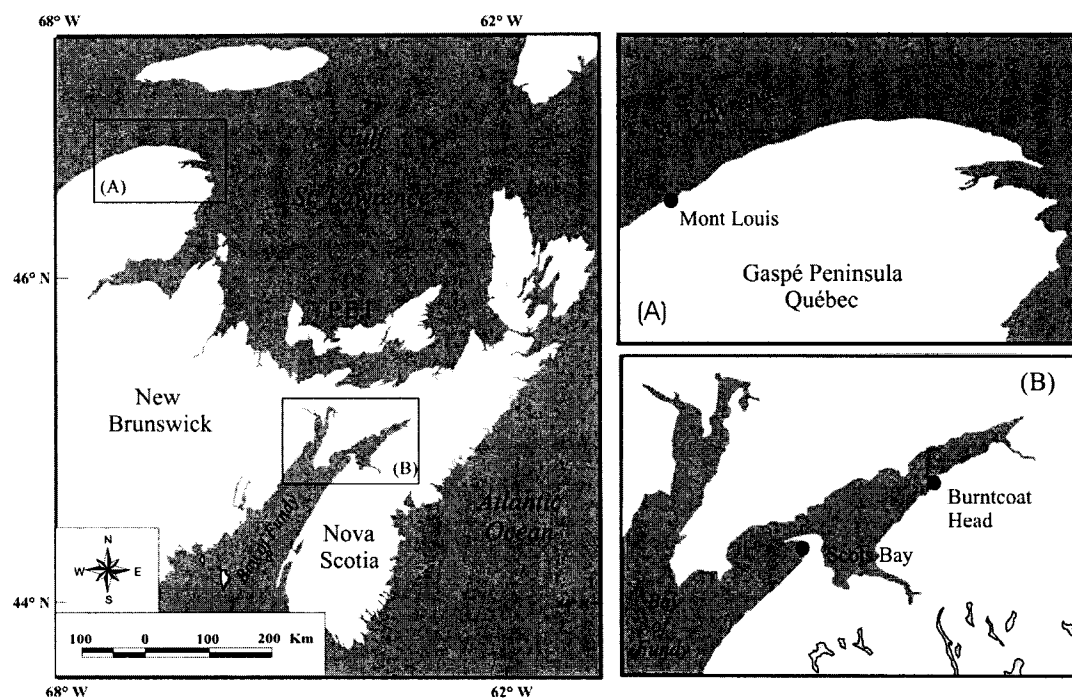
In addition to the traditional use of TMEMs to measure rates of platform downwearing in the field, they have been employed recently to study short-term variations in rock surface elevation in order to provide insights into the formative processes. Stephenson *et al.* (2004) used two TMEMs to measure diurnal variations in the elevation of a supratidal site on a greywacke platform in Australia and on an intertidal site in New Zealand. Gómez-Pujol *et al.* (in press) measured variations in surface elevation over one day at 2 hour intervals near the base of a supratidal cliff face in Australia. To supplement an experimental investigation by Kanyaya and Trenhaile (2005) on the role of wetting and drying on the shore platforms of eastern Canada, Trenhaile (2006) used a TMEM to measure the effect of intertidal elevation and air temperature and humidity on the surface expansion and contraction of drying slabs of basalt, sandstone and argillite. This work was conducted using de-ionised water in order to isolate the effect of wetting and drying by eliminating the effect of salt crystallization and other salt-related mechanisms. The present paper extends that research using three TMEMs to measure tidally induced rock surface contraction and swelling in artificial salt water in the laboratory and in sea water in the field. Short-term variations in surface elevation provide error terms for MEM and TMEM



measurements, and they may generate stresses that contribute to surface downwearing by wetting and drying and salt weathering.

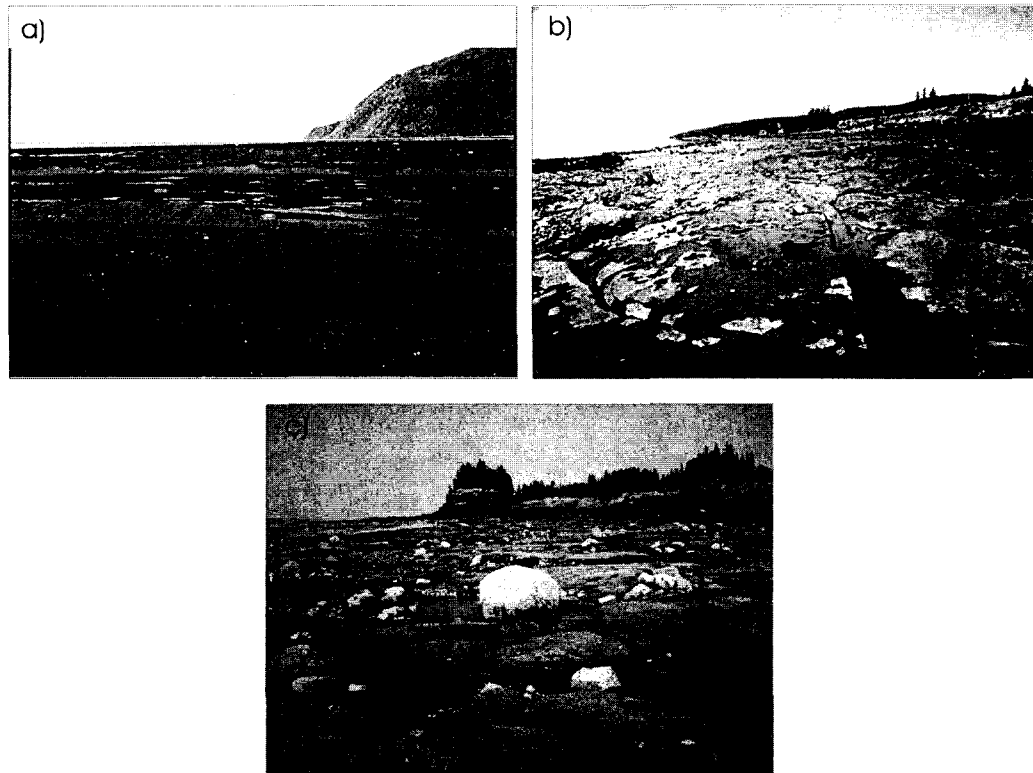
## 2.0 The study areas

The research discussed in this paper is a component of a larger investigation into the processes operating on shore platforms in eastern Canada. There are three study areas: sloping platforms in Triassic basalts at Scots Bay and in soft Triassic sandstones at Burntcoat Head in the Bay of Fundy, and a horizontal platform in Middle Ordovician argillites (low grade metamorphosed shales) at Mont Louis in Gaspé, Québec (Figures 3.1 and 3.2; Table 3.1).



**Figure 3.1.** The three study areas at Mont Louis, Québec, and at Scots Bay and Burntcoat Head, Nova Scotia.

The basalt is aphanitic to fine-grained, and largely an aggregate of anhedral augite and plagioclase feldspar laths. The sandstone mainly consists of angular quartz grains bound by a mixed carbonate (calcite) and iron oxide (hematite) cement. The argillite is mainly composed of chlorite and illite clay minerals, which have low to moderate swelling capacities, and a slaty cleavage which may contain flakes of chlorite and muscovite.



**Figure 3.2.** The three study platforms: a) Mont Louis is in argillite, b) Scots Bay is in basalt, and c) Burntcoat Head is in sandstone.

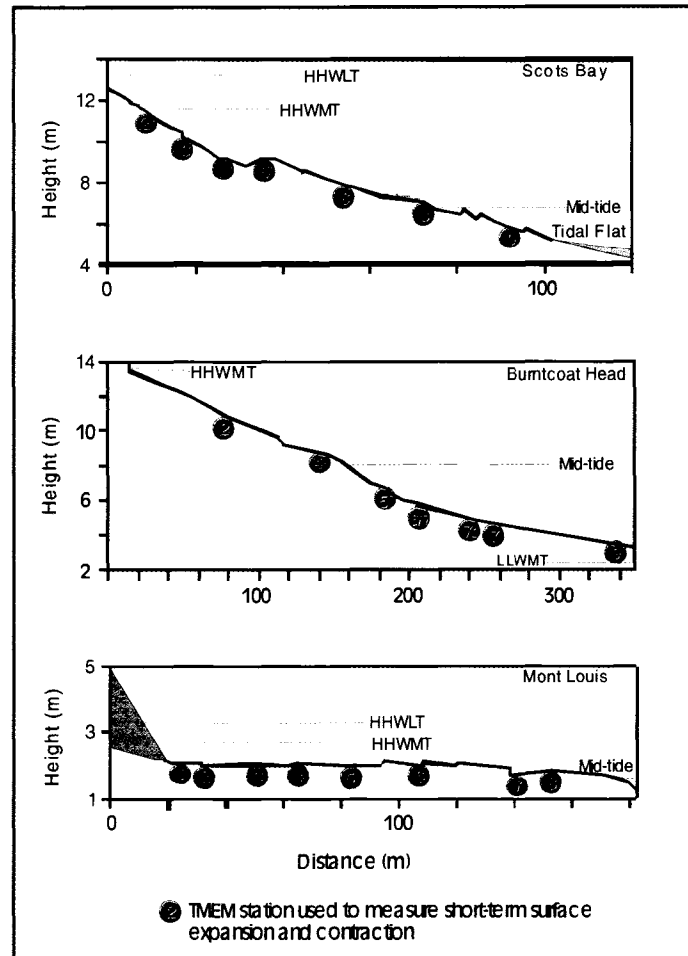
The Large Tide Range, which is defined by the Canadian Hydrographic Service as the difference between the average of the highest (HHWLT) and lowest (LLWLT) tides from each of 19 years of predictions, is 13.5 m at Scots Bay, 16 m at Burntcoat Head (the highest range in the world) and 3 m at Mont Louis. These extreme tidal conditions are rarely experienced, however, and the Mean Tide Range, the average of all the differences in high (HHWMT) and low (LLWMT) tidal levels over 19 years of prediction, is more representative of the daily conditions at each site. The Mean Tide Range is 9.9 m at Scots Bay, 11.9 m at Burntcoat Head and 1.99 m at Mont Louis. Waves in the Bay of Fundy are usually southwesterly, westerly or northwesterly. Almost half the deep water waves have a significant wave height of less than 0.5 m, and a peak wave period of less than 4 s. Ice protects the coast from storm waves from January to April. Waves generally propagate from the west and northwest on the Gaspé coast. About 15 % of the waves in deep water have a significant wave height of less than 0.5 m, and about 46 % of the peak wave periods are less than 4 s. The coast is protected by ice in winter, but it is exposed to less frequent periods of high waves in spring and fall.

**Table 3.1.** Some characteristics of the rocks from the platforms of eastern Canada

<b>Lithology</b>	<b>Vacuum saturation % weight increase</b>	<b>Compressive strength (<math>\times 10^6 \text{Nm}^{-2}</math>)</b>	<b>Mean high tide down- wearing rate (<math>\text{mm yr}^{-1}</math>) (laboratory data)</b>
Light pink to reddish sandstone, with 65% quartz, 25% hematite, 6% muscovite, 2% biotite, and 2 % gypsum. Finely laminated, compact, low grade metamorphic argillite with mineral and chemical composition similar to shale.	9.22     0.29	6     24	1.3     1.0
Medium weathered basalt with chalcedony, pyrite, plagioclase, chlorite and pyroxene.	3.36	20	0.2

The lower portion of the platform at Scots Bay lies beneath a sandy tidal flat that extends up to 1 – 2 m below the mid-tidal level. The exposed platform is from 100 to 120 m in width, and it is terminated landwards by a low grassy bluff. The platform in the study area has a concave-upwards profile, with a gradient of about  $7.5^\circ$  in the upper part,  $4.25^\circ$  in the central portion and  $3.5^\circ$  in the lower part. The platform at Burntcoat Head is between 375 and 450 m in width, and its profile in the study area is irregularly concave upwards, with a gradient of  $2.5^\circ$  in the upper portion and between  $1^\circ$  and  $1.5^\circ$  in the lower part. The cliff at the rear is steep and active, and about 20 m high. The platform at Mont Louis is horizontal, between 170 and 200 m in width, and most of its surface is about 1 m above the mid-tidal level. There is a low cliff, several metres in

height, at the back of the platform, with a steep coarse-grained beach at its foot. The platform terminates abruptly seawards in a low tide cliff of unknown height (Figure 3.3).



**Figure 3.3.** Platform profiles and location and number of the TMEM stations used to measure short-term changes in surface elevation.

### 3.0 Methods

A micro-erosion meter consists of an engineer's gauge that measures the downward extension of a probe, mounted on a low, triangular frame. When in use, the legs of the frame are placed on three bolts (constituting an MEM or TMEM station) that are permanently embedded in the rock surface (High and Hanna, 1970; Robinson, 1976). Three TMEMs were used in the present study. Although TMEMs can be used to make numerous measurements within the triangular area between the three bolts at each station (Trudgill et al., 1981; Stephenson, 1997), only seven were made at each of the stations installed on the slabs and on the platforms of eastern

Canada.

In the laboratory, TMEM stations were installed in slabs of basalt, sandstone and argillite (about 30-40 x 20-30 x 8-12 cm in size) obtained from the platforms in the three study areas. Commercial artificial sea water, produced by Aquarium Systems Inc, was used in these experiments: this water has an approximate salinity of 35 ‰ and contains 28 ions and elements in concentrations that are similar to their occurrence in natural seawater. The slabs were immersed in this water for 1, 6 or 11 hours, and then exposed to air for the remainder of the twelve-hours of a semi-diurnal tidal cycle, thereby simulating high, mid- and low tidal conditions, respectively. To remove excess water, slab surfaces were dried with a cloth when first removed from the water, and the TMEMs were then placed on the stations and used to record, to within 0.01 mm, positive (contraction) or negative (expansion) changes in the elevation of the rock surfaces as they dried: air temperature and relative humidity were also recorded.

Single slabs of basalt and sandstone were used in the laboratory experiments, but there were two slabs of argillite. The first slab (slab 1) was also used by Trenhaile (2006) to study wetting and drying, using de-ionized water. This slab had more open cleavage than the second slab, and it disintegrated during the early part of the present research. Most of the present work was conducted therefore on a second, more cohesive, or less weathered, argillite slab (slab 2). The closed nature of the cleavage planes in this slab made it more difficult for water and salt to penetrate the cleavage planes than in the original slab, although both slabs had a very low ability to absorb water through their voids (see ‘vacuum saturation weight increase’ in Table I).

Work was conducted in the field over 10 days in mid-July, 2005. To measure changes in surface elevation in the study areas, the three TMEMs were placed on TMEM stations at various intertidal elevations, as soon as the rock became accessible from beneath the ebbing tide. Measurements were then made at frequent though irregular intervals during the period of exposure, according to the rate of surface elevational change. Because of weather conditions and failing light, however, it was often impossible to continue taking readings at stations near the high tidal level up to the point at which they were about to be submerged by the rising tide.

To measure rates of surface downwearing at various points within a TMEM station, the instrument must be moved to different positions within its triangular frame. The errors that usually arise from trying to repeat measurements through time at the same point on the surface, however, would tend to mask the small, short-term variations in elevation caused by the rock absorbing and desorbing water that are the subject of this investigation. In the only previously published studies of short-term changes in rock surface elevation, Stephenson *et al.* (2004) and Gómez-Pujol *et al.* (in press) removed the TMEMs after each measurement and employed

statistical methods and station means to manage the errors that arise from periodically replacing the instruments in the same locations. A different technique was used by Trenhaile (2006) and in the present study, whereby the three TMEMs were kept mounted on their studs during the drying period, in the laboratory and in the field, with the tips of their probes maintained at exactly the same points on the rock surfaces

There are advantages and disadvantages to both methods. Stephenson *et al.*'s technique allows many points to be measured at each TMEM station in a given period of time, whereas the technique used in the present study provides measurements at only one point over the same period. Therefore the present technique is very time consuming, and despite using three TMEMs, this study required more than 40 days of twelve-hour measurement in the laboratory and 10 days in the field. Conversely, keeping the TMEMs on the same points provides very precise point data that are free of the measurement errors and the effects of surface erosion that arise through repeatedly moving and repositioning the tip of the instrument probe. The technique that is used in this study therefore allows data from different points within a TMEM station to be analyzed and compared.

Other supplemental data that are relevant to this investigation are being measured in the laboratory and in the field. This work has been published in several papers (Trenhaile and Kanyaya, 2004; Kanyaya and Trenhaile, 2005; Trenhaile, 2006; Trenhaile *et al.*, in press), and to avoid unnecessary duplication, the reader is referred to these publications for more detailed descriptions of the relevant methodologies. Three ancillary components are used in this study:

- (1) Using tidal simulators and artificial sea water, more than 220 argillite, basalt and sandstone rock cores and cubes have been subjected, under real time conditions, to more than 1,000 tidal cycles over a 17 month period. Changes in rock sample weight at the high, mid- and low tidal levels were converted into rates of surface downweathering based on sample density and surface area.
- (2) Using TMEMs, rates of platform downwearing have been measured at more than 70 stations installed along surveyed, shore-normal profiles in the three study areas, for periods ranging between 1 and 3 years (Table 3.2).

**Table 3.2.** Descriptive statistics for annual, TMEM-measured changes in surface elevation at individual points at 46 active (records of more than 2 years) TMEM stations in eastern Canada<sup>1</sup>

	Burntcoat	Scots Bay	Mont Louis
Mean	0.94	0.20	0.10
Standard Error	0.12	0.06	0.03
Median	0.25	0.16	0.05
Mode	0.04	-0.09	-0.04
Standard Deviation	1.20	0.63	0.33
Kurtosis	-0.55	13.43	3.02
Skewness	0.76	2.25	1.08
Minimum	-1.05	-1.50	-0.83
Maximum	4.26	4.18	1.24
Count	105	119	97
Confidence Level(0.95)	0.23	0.11	0.07

<sup>1</sup> Positive surface changes refer to lowering of the surface by downwearing or by contraction, and negative values to surface rising or expansion.

- (3) An N-type Schmidt Rock Test Hammer was used to measure rock hardness at each of the TMEM stations in the study areas. Twenty-five measurements were made at each station and Chauvenet's Criterion was used to reject observations that, for N number of values, have a deviation from the mean greater than that corresponding to a  $\frac{1}{2} N$  probability (Göktan and Ayday, 1993; Dickson *et al*, 2004). The mean of the remaining rebound values was then used to represent the strength of the rock at each station.

## 4.0 Results

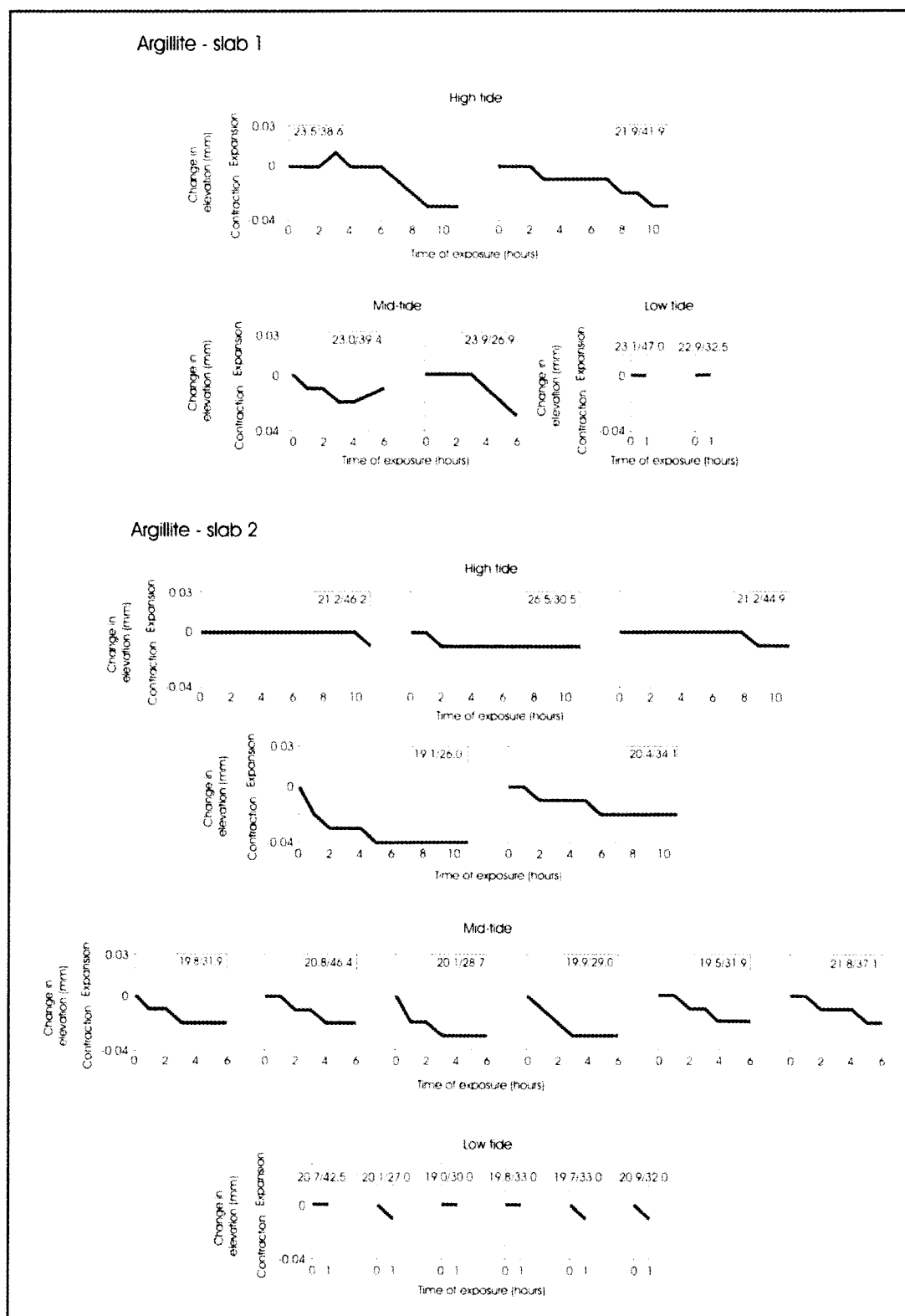
The greatest changes in surface elevation in the laboratory experiments were usually recorded by the two argillite rock slabs, although the magnitude and occurrence of these changes were quite variable (Figure 3.4). There were occasional instances of surface expansion (the surface rising) in slab 1, possibly as a result of tilting of the loose surface layers over open cleavage planes, but only contraction (lowering of the surface) was recorded as the second slab dried. Changes in surface elevation were generally a little lower in the basalts than in the argillites (Figure 3.5). Of the 32 runs that were made with the basalt slab, there was no change in elevation at the low tidal level, and changes only occurred in a minority of runs at the mid- and high tidal levels: the greatest amount of contraction at any level was only 0.02 mm. A change in

surface elevation was only recorded once (contraction of 0.01 mm at the high tidal level) in 23 runs with the sandstone slab: this is consistent with a previous study in which it was found that the sandstone was also unaffected in otherwise similar wetting and drying experiments using de-ionized water (Trenhaile, 2006).

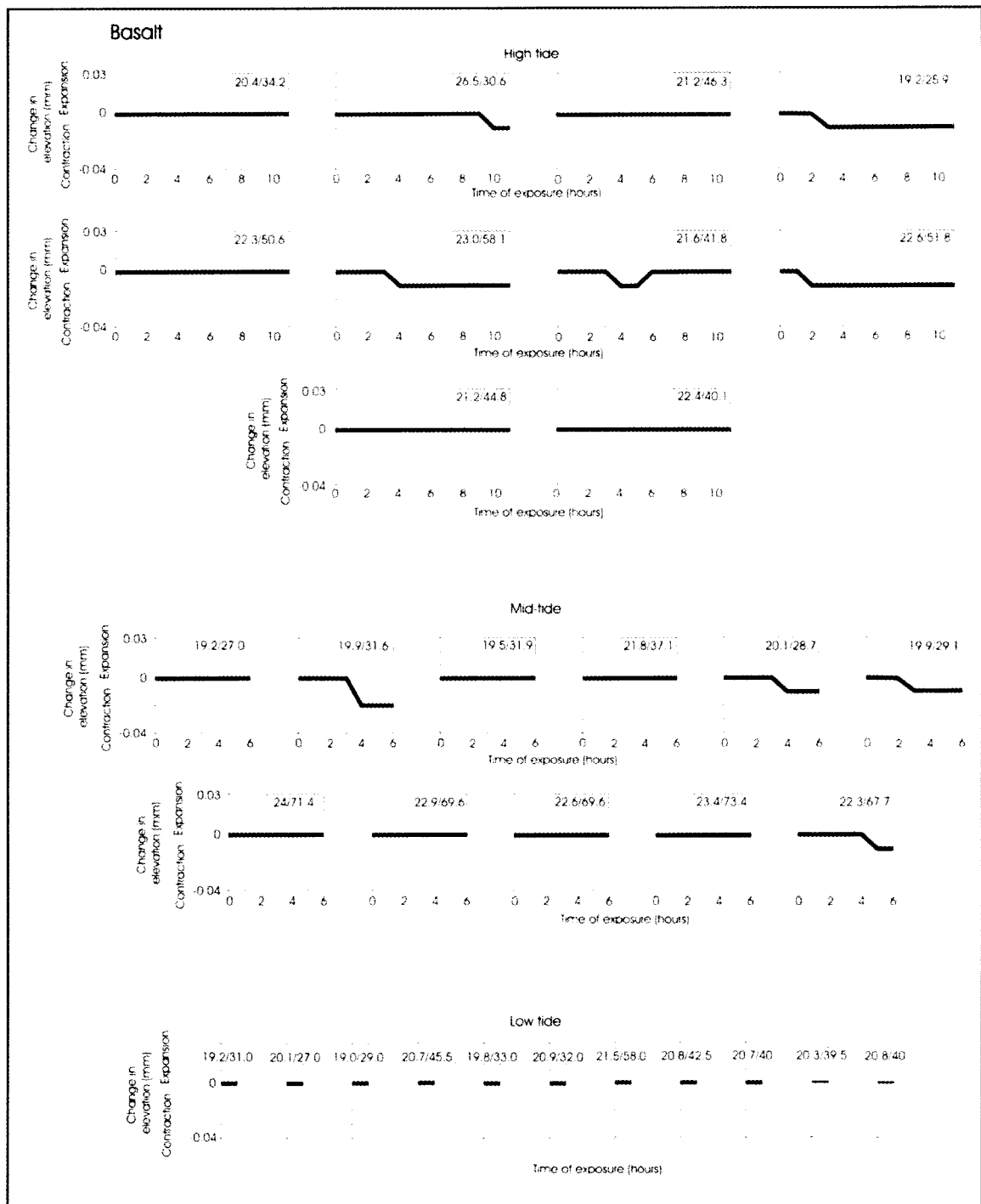
Rock contraction, and occasionally expansion, events in the field were of generally similar magnitude as in the laboratory, and they exhibited the same degree of variability (Figure 3.6). The main difference between the field and laboratory measurements was therefore that surface contraction, ranging up to 0.03 mm, was fairly common in the sandstones at Burntcoat Head.

Tidal elevation determines the relative length of the periods of exposure and immersion, and consequently the amount of time available to a rock surface for wetting and drying and for salt crystallization. The rocks that were used in this study only require fairly brief periods (1 to 2 hours) to absorb their maximum amounts of water while immersed in shallow water, but they require much longer periods of exposure to dry completely (Kanyaya and Trenhaile, 2005). As the period of exposure and drying increases with elevation within the intertidal zone, one might therefore expect that changes in surface elevation would increase from the low to the high tidal level. There was a significant relationship, with a moderate correlation, between contraction amounts and tidal elevation in the argillites in the laboratory, and although there is almost no variation in elevation on the sub-horizontal shore platform at Mont Louis, the relationship between contraction amounts and tidal elevation was also significant when the laboratory and field data were combined. The same relationships appeared in the basalts, although there was often no rock surface contraction in the laboratory experiments. There was no significant correlation between the amount of surface contraction and tidal elevation in the basalts in the field at Scots Bay, possibly in part because the lower portion of the platform is covered by a tidal flat. Sandstone contraction tended to increase with tidal elevation in the field, but the sample number was low and the relationship was not significant (Figure 3.7).

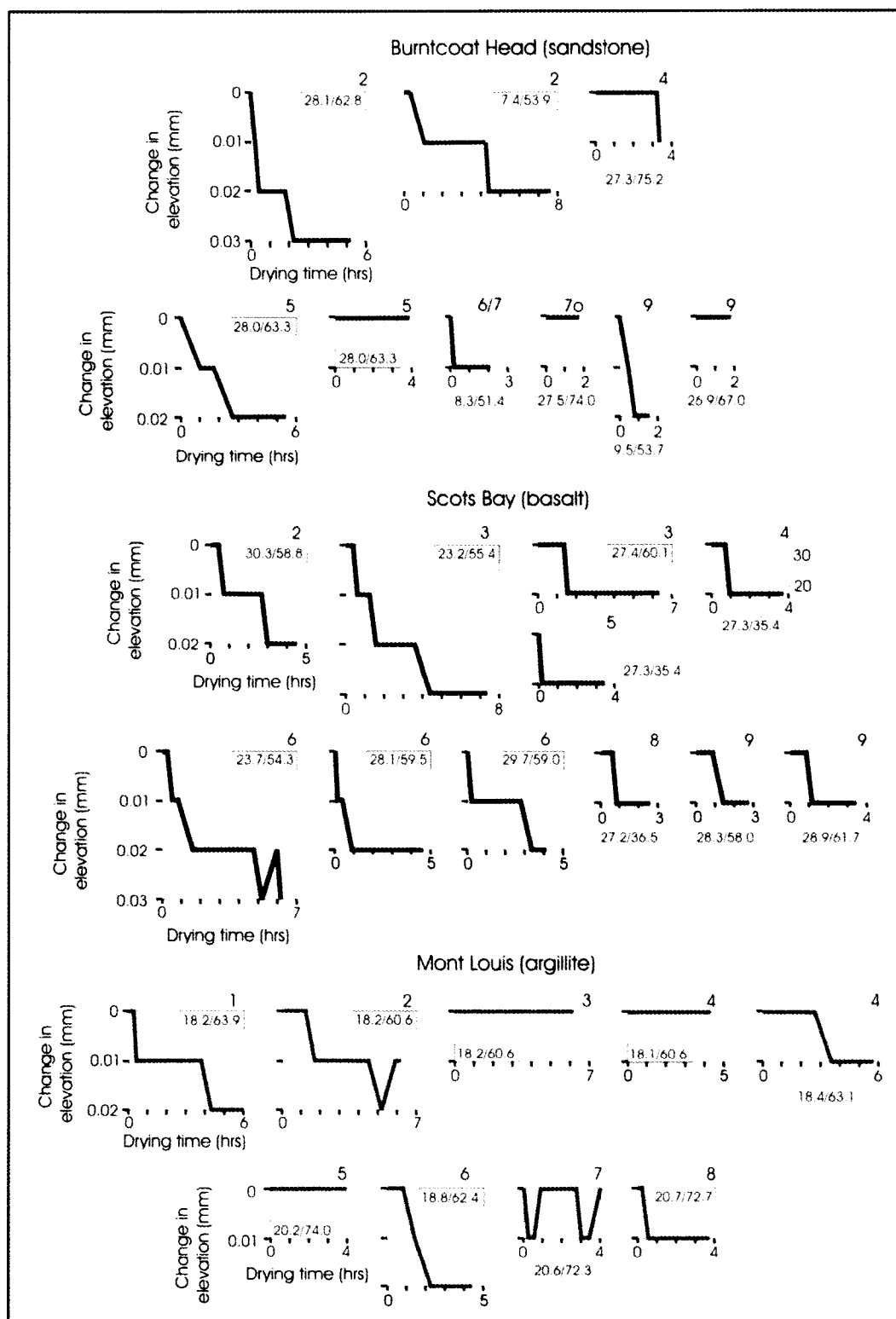




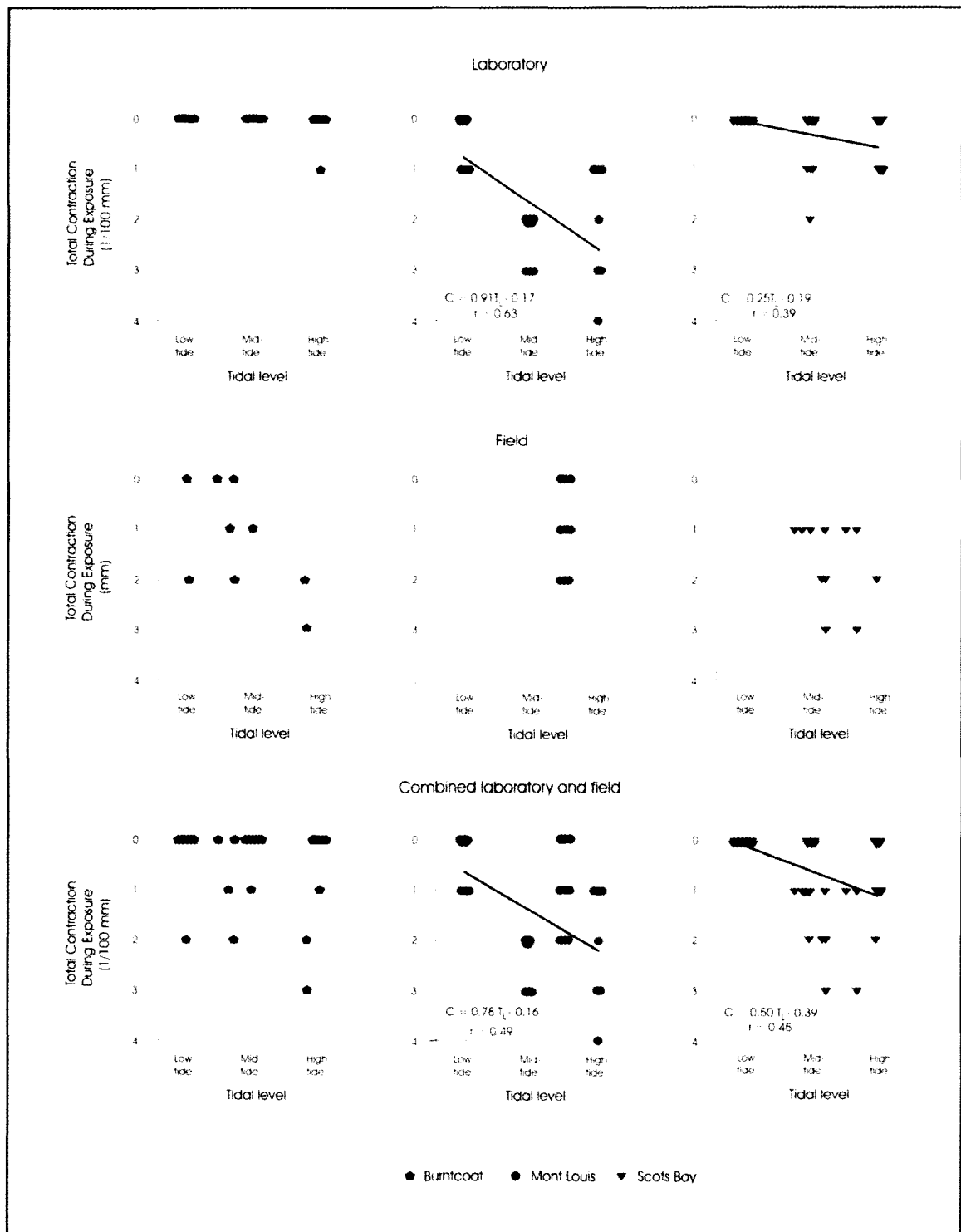
**Figure 3.4.** Argillite surface changes in the laboratory. The two boxed numbers separated by a slash in figures 4 – 6 and 11-12 show the mean temperature and relative humidity of the air, respectively.



**Figure 3.5.** Basalt surface changes in the laboratory.

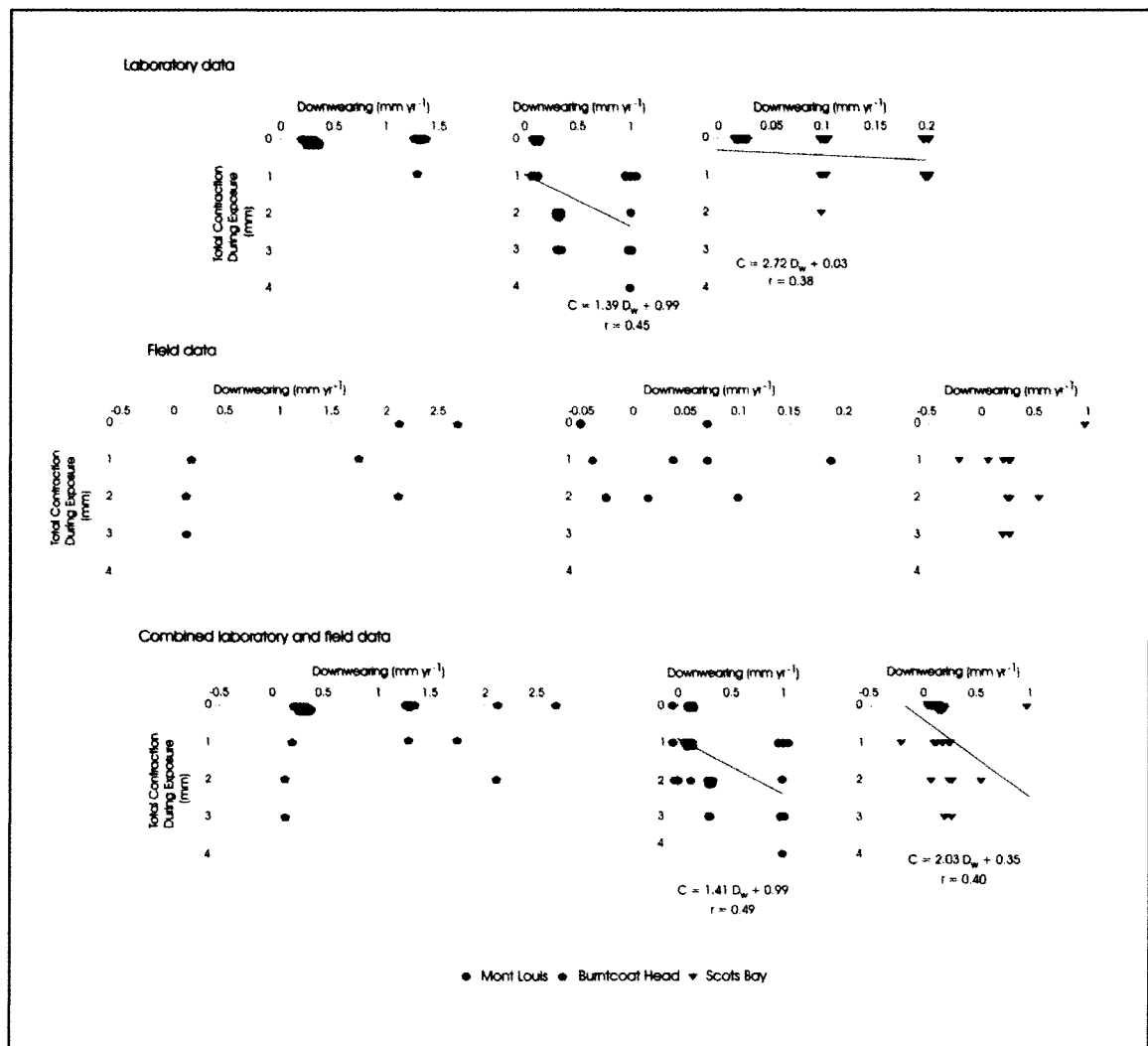


**Figure 3.6.** Changes in surface elevation in the field.



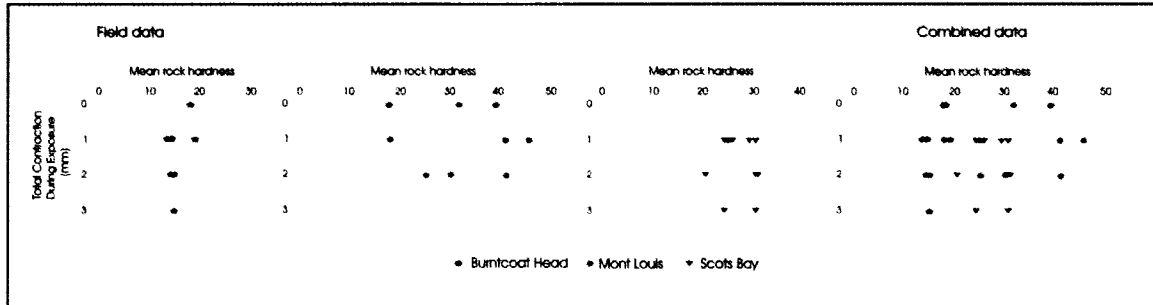
**Figure 3.7.** The relationship between rock contraction ( $C$ ) and tidal elevation ( $T_L$ ) in the laboratory and the field.  $T_L = 1, 2$  and  $3$  at the low, mid- and high tidal levels, respectively. Correlations ( $r$  values) are significant at the  $p = 0.05$  level.

The stresses associated with tidally induced expansion and contraction may cause, or contribute to, surface downwearing. To investigate this possibility, rates of downwearing calculated from the breakdown of rock samples in tidal simulators in the laboratory and measured directly with TMEMs in the field (Trenhaile *et al.*, in press), were plotted against the amount of surface contraction recorded at each TMEM station in the laboratory and field (Figure 3.8). Although the number of data points is fairly low, rates of downwearing generally increased with the amount of contraction in the argillites and in the basalts, but there was no relationship between these variables in the sandstones.



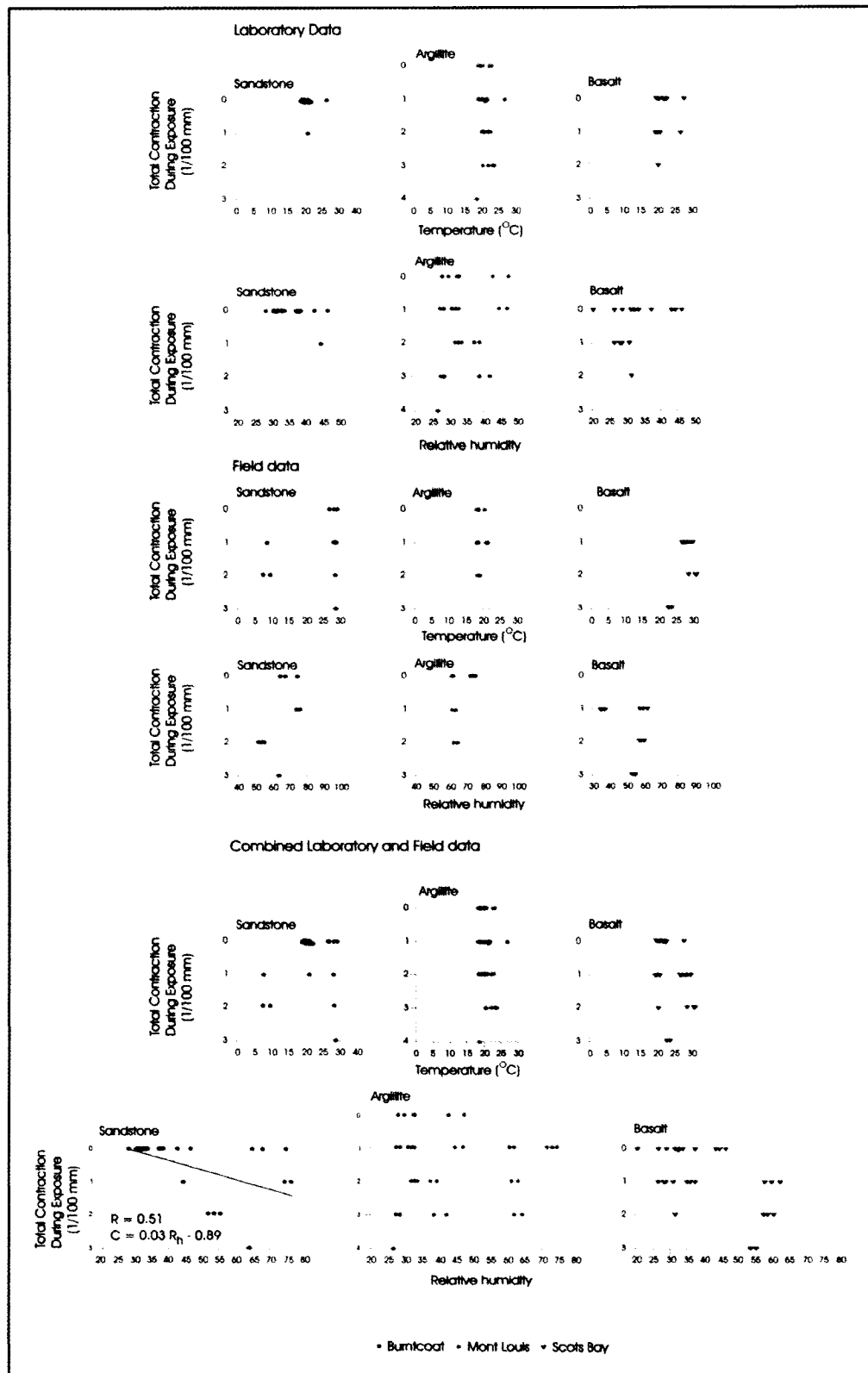
**Figure 3.8.** The relationship between rock contraction during tidal drying in the laboratory ( $C$ ) (using artificial sea water) and mean annual platform downwearing rate ( $D_w$ ) in the three study areas. Correlations are significant at the  $p = 0.05$  level.

Kanyaya and Trenhaile (2005) found that the rate of rock downwearing by tidal wetting and drying (using de-ionized water) decreased with the compressive strength of the rock. There was no relationship, however, between rock hardness, measured with a Schmidt Rock Test Hammer, and drying rock contraction in the field for the three rock types, or between these variables when the rock types were combined to provide a wider range of hardness values (Figure 3.9).



**Figure 3.9.** Rock contraction and rock hardness (Schmidt Rock Test Hammer rebound values) in the field.

It might also be expected that the rate and amount of rock drying and consequently surface contraction in the intertidal zone would increase with the temperature and decrease with the humidity of the air. The laboratory work was conducted under room conditions that ranged between about 18 and 28°C in temperature, and generally from about 26 to 47 % in relative humidity, although a few basalt experiments were conducted under more humid conditions. There was no relationship between the amount of surface contraction and room conditions for all three rock types (Figure 3.10). Measurements were made in the field over 10 days in mid-July, 2005, when mean temperatures were generally between 18 and 30°C: temperatures varied only by about 1-5°C over each daily measurement period. There was no consistent relationship between surface contraction and air temperature and relative humidity in the field. This could be partly attributed to the lack of much variation in weather conditions at Mont Louis and Scots Bay, although there was also no relationship at Burntcoat Head, where temperatures ranged between 6 and 29°C. Even when the field and laboratory data were combined in order to extend the range of air temperature and humidity that was experienced, there was only one statistically significant relationship, which suggested, contrary to expectations, that sandstone contraction increases with relative humidity (Figure 3.10). Further analysis of the data showed that there was no relationship between the amount of surface contraction and the range of temperature and relative humidity experienced during each daily measurement period.

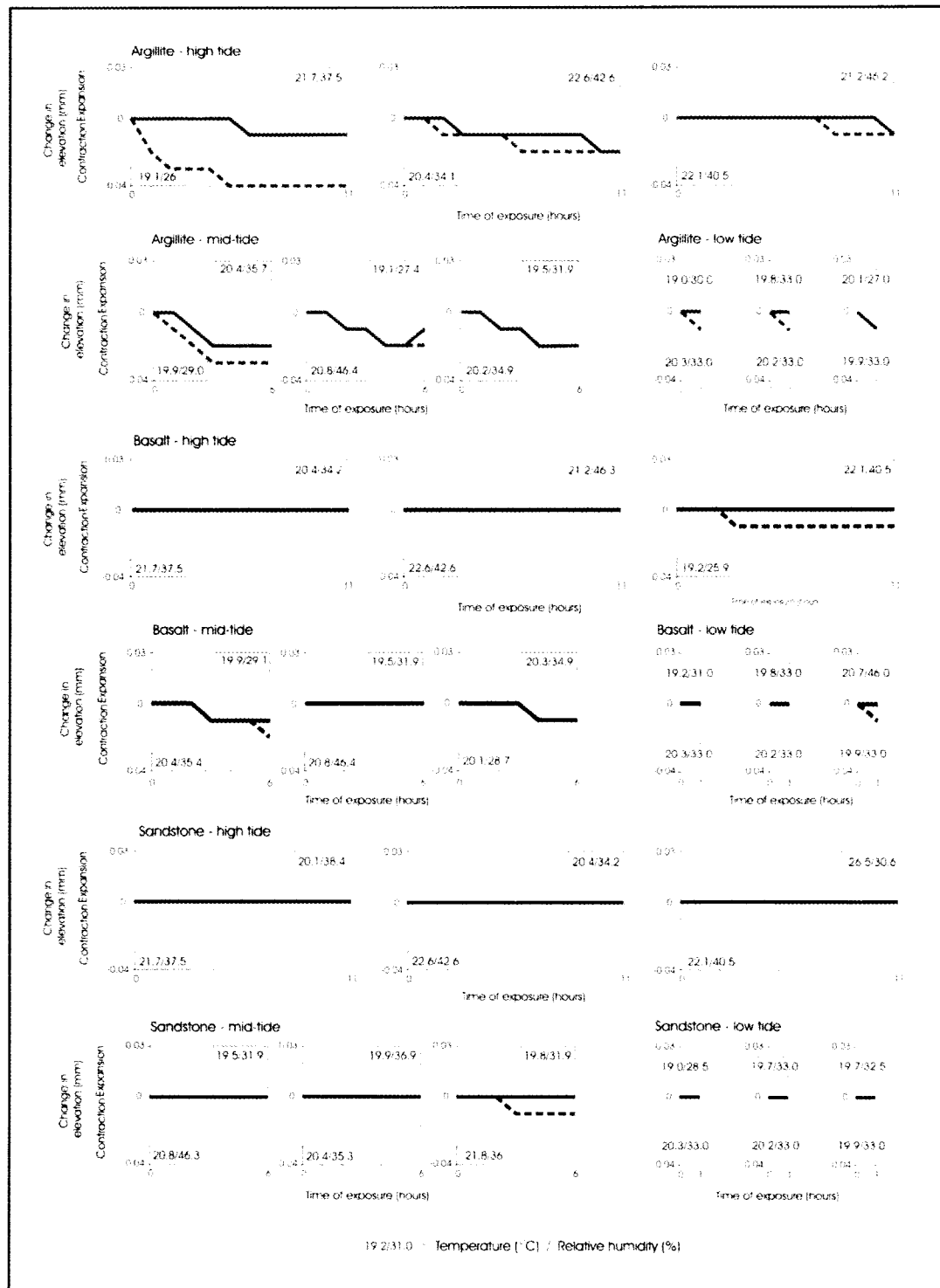


**Figure 3.10.** Rock contraction ( $C$ ) and air temperature and humidity ( $R_h$ ) in the laboratory and in the field. The sandstone correlation is significant at the  $p = 0.05$  level.

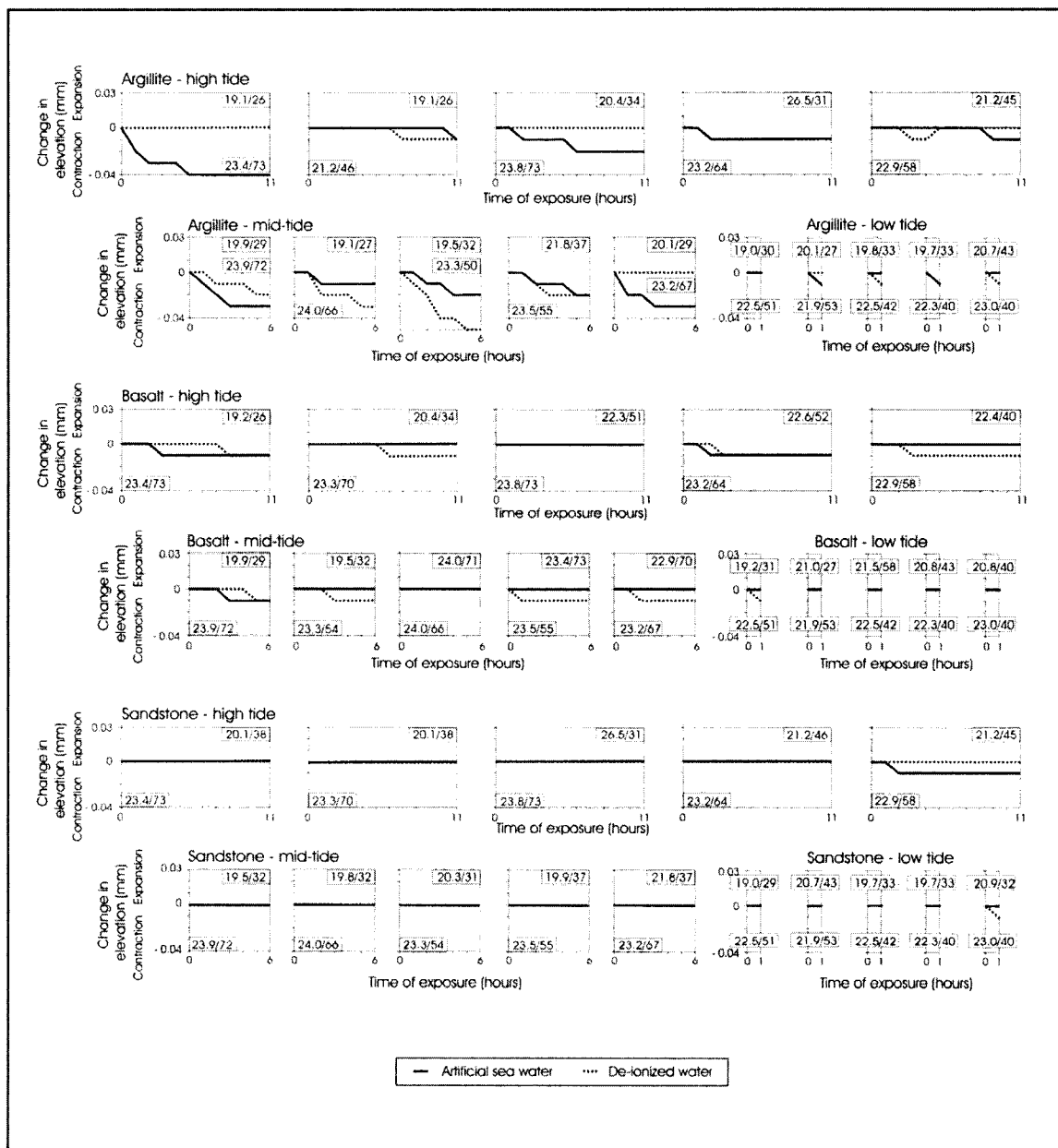
To determine whether the general lack of strong correlations between contraction and other factors was due to random elements in the data, twenty-seven runs were repeated in the laboratory at the same points on the rock surface (Figure 3.11). Although there were some differences in the air temperature and humidity, the original and repeat runs were otherwise identical. The amount of contraction was generally similar in the original and the repeat runs. There was only one marked difference, one argillite run producing 0.01 mm of surface contraction and the second a contraction of 0.04 mm (see the first example in Figure 3.11). The reason for the difference in these runs is unclear, as temperatures were similar and although there was some difference in humidity (37.5% and 26.0%), similar or greater differences in humidity did not markedly affect other comparisons in argillite, basalt or sandstone.

Changes in surface elevation could be the result of wetting and drying, or salt crystallization or some other salt-related mechanism. To try to identify the responsible mechanism, 15 of the salt water runs for each of the three rock types were repeated in de-ionized (fresh) water, using the same points at each TMEM station for the comparisons. The rock surfaces contracted as they dried in a generally similar way in the fresh and artificial sea water experiments (Figure 3.12). There was no surface contraction in salt or fresh water in 27 of the 45 runs and contraction was greater in fresh than in salt water in 11 runs. Contraction was lower in fresh than in salt water in only 7 runs, which were mainly in the argillite. Because the fresh water experiments were conducted during the late spring, a few months after the salt water experiments, air temperatures were often a few degrees higher during the fresh water runs. There was no apparent relationship, however, between temperature and differences in surface contraction in the fresh and salt water experiments. There were also differences of up to almost 50 % in the relative humidity of the air during the two types of experiments. The air was usually more humid during the fresh water experiments, although relative humidity was occasionally up to almost 20 % higher in the salt than in the fresh water experiments. Nevertheless, differences in relative humidity in the fresh and salt water experiments did not appear to have any consistent effect on the amount of contraction experienced in the two types of experiment.





**Figure 3.11.** Examples of duplicate measurements at the same point on the rock surface under the same tidal conditions. The two boxed numbers, separated by a slash, show the mean temperature and relative humidity, respectively. The upper box is for the solid line and the lower box for the dashed line. Where there is only one line visible, the two runs were identical. Argillite laboratory data are only for slab 2.



**Figure 3.12.** Comparison between runs made at the same points at TMEM stations in artificial sea water and in de-ionized water. The two boxed numbers, separated by a slash, show the mean temperature and relative humidity, respectively. The upper box is for salt water and the lower box for de-ionized water. Where there is only one line visible, the two runs were identical.

## 5.0 Discussion

The only previous use of TMEMs to measure short-term changes in platform surface elevation was by Stephenson *et al.* (2004) and Gómez-Pujol *et al.* (in press). The present study investigated even shorter-term variations in the surface of intertidal rocks in the laboratory and in the field while the rocks were exposed during single tidal cycles.

Stephenson *et al.* (2004) measured day to day variations in surface elevation at a supratidal, greywacke TMEM station in Victoria, Australia, and at an intertidal, mudstone TMEM station at Kaikoura, New Zealand. Measurements were made for five days at numerous points on the surface at each station, three hours after high tide, and then averaged to produce a station mean. Mean elevation change at each daily reading in Victoria ranged from an elevation of about 0.27 mm to a contraction of 0.053 mm, and in New Zealand from an elevation of about 0.02 mm to a contraction of 0.03 mm. These mean station contraction values are similar to the amount of contraction measured in the present study at individual points on the surface, while exposed during single tidal cycles. Maximum changes between daily readings of up to 3.4 mm in Australia and about 1.1 mm in New Zealand, however, are much greater than any of the short-term changes recorded within tidal cycles in the laboratory or in the field in eastern Canada. Gómez-Pujol *et al.* (in press) recorded surface lowering, or contraction, at two-hour intervals for one day on fine-grained sandstones at a supratidal TMEM station in Australia: the amount of surface lowering ranged up to 0.126 mm during the day. Furthermore, whereas there was little short-term elevation of the rock surface in the present study, this was a common occurrence during the day (Gómez-Pujol *et al.*, in press), and from one day to the next (Stephenson *et al.*, 2004), in Australasia.

Stephenson *et al.* (2004) and Gómez-Pujol *et al.* (in press) found that the processes responsible for diurnal changes in surface elevation in Australia operate at the level of the individual TMEM points, rather than across the whole station. This conclusion is consistent with the present study, which was characterized by spatially variable changes in surface elevation within each TMEM station, in the field and in the laboratory. Conversely, the results of the present study are not consistent with the day to day changes in elevation recorded in New Zealand, where the whole site experienced distinct changes, possibly involving cycles of expansion or contraction (Stephenson *et al.* 2004). The similar behaviour of the intertidal Canadian laboratory and field stations and the supratidal Australian stations, rather than of the intertidal Canadian and New Zealand stations, suggests that short-term changes in surface elevation probably reflect variations in rock mineralogy, grain size and void characteristics, rather

than the frequency of wetting and drying intervals or the relative importance of wetting and drying or salt crystallization mechanisms.

Stephenson *et al.* (2004) attributed changes in surface elevation to the effects of wetting and drying. Trenhaile (2006) conducted similar experiments on rock slabs to those reported in the present study, except that the rocks were subjected to simulated tidal cycles in de-ionized rather than in salt water. Wetting and drying with de-ionized water caused the argillite (slab 1) and basalt slabs to expand and contract by up to 0.14 and 0.04 mm, respectively, but wetting and drying did not produce any elevational changes in the sandstone. Although these experiments suggested that changes in surface elevation are greater in fresh than in salt water, the data are not directly comparable with the results of the present study because they were derived from different points on the rock surface, and in some cases from different rock slabs. In the study reported here, changes in surface elevation were measured at exactly the same points in fresh and salt water (Figure 3.12). With the possible exception of argillite in the upper part of the intertidal zone, however, these runs produced no clear evidence that rocks contract more frequently or by greater amounts in salt than in fresh water, thereby providing support for the contention that short-term expansion or contraction events in the intertidal zone are primarily the result of wetting and drying.

All the laboratory experiments reported in this paper were based on the assumption that the rocks experience two periods of tidal immersion and two periods of exposure every 24 hours: most of the TMEM stations are also submerged twice by the tides every 24 hours. Wetting and drying may be more important than salt-related mechanisms in the zone of frequent submergence between the neap high and low tidal levels because the fairly short periods of exposure inhibit salt crystallization in the rock voids. It remains to be determined, however, whether wetting and drying is also more important than salt crystallization in the upper portions of the intertidal zone and in the lower portions of the supratidal zone, where the intervals between extreme tides or storm events may range from several days to several weeks or more.

### **5.1 Short- versus long-term changes in surface elevation**

Surface contraction ranged between 0 and 0.04 mm in the laboratory and between 0 and 0.03 mm in the field. These figures are an order of magnitude lower than most mean annual downwearing amounts measured with TMEMs, in the field or by tidal simulation in the laboratory (Trenhaile *et al.*, in press). This suggests that, in general, TMEM measurements in the study areas can be made at any time during the period of tidal exposure, without their being significantly

affected by the amount of water in the rocks. This assumption is less valid for stations that experience very slow rates of downwearing between measurement intervals, or when considering the downwearing of individual points within TMEM stations, as opposed to station means.

An analysis was made of the annual amount of change in surface elevation, largely through downwearing, that has occurred at each of the seven measured points at each of the 46 active TMEM stations (measured for at least 2 years) in the field (Table 3.2). From one year to the next, changes at 7 % of the points in the sandstone and basalt and at 26 % of the points in the argillite were equal or less than 0.04 mm: annual surface lowering was most common but there were also numerous examples of surface elevation, especially in the argillites. More than a quarter of the annual changes in elevation in the argillites may therefore result from temporary, short-term, tidally induced fluctuations rather than from longer-term surface expansion or permanent changes owing to surface downwearing. Even in the sandstones and basalts, the data suggest that small changes in surface elevation cannot be considered, necessarily, to be indicative of long-term or permanent changes. Furthermore, because of lower amounts of downwearing, the relative importance of tidally induced swelling and contraction increases with measurement frequency, and it may be an important consideration when TMEM measurements are made at monthly or seasonal intervals.

## **5.2 Do short-term changes in surface elevation cause long-term surface downwearing?**

Intertidal downwearing rates in eastern Canada are reasonably consistent with those recorded in the laboratory experiments using artificial sea water (Table 3.3). This suggests that frost, ice and bio-erosional mechanisms, which were not represented in the laboratory experiments, are not the dominant downwearing agents in the study areas, and that downwearing can be mainly attributed to sea water wetting and drying, albeit assisted in a few places at Burntcoat Head, by abrasion. The question therefore arises as to whether this downwearing, through surface spalling and granular disintegration, can be attributed, in whole or in part, to semi-diurnal stress fields generated by tidally induced surface expansion and contraction.

**Table 3.3.** Downwearing rates in the field and in artificial sea water (mm yr<sup>-1</sup>)

	Field	Laboratory		
		High tide	Mid-tide	Low tide
Burntcoat Head <sup>1</sup>	0.94	1.32	0.28	0.32
Scots Bay <sup>2</sup>	0.20	0.2	0.1	0.02
Mont Louis <sup>3</sup>	0.10	1	0.30	0.11

<sup>1</sup> The field value for Burntcoat Head is the mean of 15 active TMEM stations arraigned along a profile extending from the high to the low tidal level. In addition to salt and wetting and drying effects, abrasion is also important at some of these stations.

<sup>2</sup> The exposed platform surface at Scots Bay only extends between the high and mid-tidal levels.

<sup>3</sup> All the rocks on the horizontal platform at Mont Louis are a little above the mid-tidal level.

There were almost no short-term changes in the surface elevation of the sandstone in the laboratory, presumably because the porous nature of this coarse-grained rock permits it to absorb water without generating expansive pressures (Table 3.1)(Trenhaile, 2006). Therefore, granular disintegration of the sandstones in the laboratory is probably the result of chemical or salt weathering of the hematite and calcite cement. This mechanism must also be important in the field, where abrasion also assumes an important role at some TMEM stations. In contrast with the laboratory experiments, however, the sandstones at Burntcoat Head do expand and contract in response to tidal immersion and exposure, and there seems to be a general tendency, although it not statistically significant at the  $p = 0.05$  level, for the amount of expansion to increase with the length of the exposure period from the low to the high tidal level (Figure 3.7).

Although their experiments were conducted over only one day and at a single supratidal TMEM station, Gómez-Pujol *et al.* (in press) found that there was a general tendency for rock surface contraction in the morning when temperatures were rising and humidity was falling. They concluded that changes in surface elevation at this site are the result of the expansion and contraction of lichen thalli, in response to variations in the humidity of the air. Although there has been no microscopic analysis of the rocks in eastern Canada, the only visible microflora is the uppermost portion of the intertidal zone at Burntcoat Head, where there is some Chlorophytic algae, and possibly Cyanophytic algae and associated fungi and lichen. As in the morning in Australia (Gómez-Pujol *et al.*, in press), the rock at Station 2 at Burntcoat Head contracted by 0.02 mm on a day when temperatures increased and relative humidity decreased during the measurement period, but the rock also contracted by 0.03 mm at the same station, albeit at a different point on the surface, on another day when there was little variation in temperature or

humidity (Figure 3.6). The general lack of visible microflora in the intertidal zone in eastern Canada, presumably because of ice scour and severe winter conditions, further suggests that expansion of the roots of endolithic microflora is not important in the present study.

The tendency for sandstone contraction to increase with decreasing temperature at Burntcoat Head (Figure 3.10) implies that contraction is not the result of the evaporation of absorbed water, which would be expected to be greater at higher temperatures. The possible inverse relationship between contraction and temperature suggests that sandstone contraction in the field may result from the adsorption and desorption of water directly from the air. Positively charged water molecules in humid air become attached to negatively charged clay particles within the rock. The mechanism is temperature-dependent, the maximum amount of water being adsorbed directly from the air at temperatures between 20 and 25°C (Hudec 1977). Exposed intertidal rocks may therefore expand at higher temperatures and contract at lower temperatures, which is consistent with sandstone behaviour in the field. Temperature-dependent wetting and drying is thought to be most effective in fine-grained, clay-rich rocks. The water in the macrotidal Minas Basin is very muddy, however, and clay accumulation in the rock might serve to reduce the size of the near-surface voids in the sandstones. Abundant clay minerals would then promote rock expansion and contraction through water adsorption and desorption, which would have been facilitated at Burntcoat Head by fairly large differences in mean air temperature from one measurement period to the next. As the TMEMs were allowed to equilibrate with ambient air temperatures before any measurements were made, and because there was only a 1 to 5°C change in daily temperature during all the measurement periods at Burntcoat Head, it is unlikely that temperature induced expansion and contraction of the metal TMEMs was a significant factor.

The original argillite slab (slab 1), used in the fresh water experiments of Trenhaile (2006) and for a few initial measurements in the present study, was much more weathered than the second slab, which was used in most of the experiments reported in this paper. The horizontal cleavage planes in the first slab were more open and provided much easier access to water penetration than in the second slab. In contrast to the second slab, which only experienced contraction in the laboratory, the first slab surface expanded and contracted, and although the maximum surface change in artificial sea water was similar in the two slabs (up to 0.04 mm), the first slab tended to expand by greater amounts and more frequently than the second slab. The friability of the surface made it impossible to install TMEM stations in the most weathered sections of the argillite outcrops at Mont Louis, and the recorded changes in surface elevation in this area are therefore from rocks that are more similar to the second than to the first argillite slab used in the laboratory. Most argillite breakdown in the laboratory and in the field is by splitting

along cleavage plains and other discontinuities. The argillites have very low porosity (Table 3.1), and in the laboratory freshly cut argillite rock cores remain essentially intact, in de-ionized (Kanyaya and Trenhaile, 2005) and in artificial sea water, for at least 6 months, until weathering is able to open the cleavage planes sufficiently to allow the water to enter the rock. This is consistent with the differences in expansion-contraction behaviour between the weathered (slab 1) and essentially unweathered (slab 2) argillite slabs and with the low, short-term changes in elevation recorded in the essentially unweathered argillite surfaces in the field. Another factor that supports the contention that argillite downwearing is, at least in part, the result of tidally induced expansion and contraction as the rocks absorb and desorb water, is the increase in both the amount of contraction during drying and in the rate of downwearing with elevation within the intertidal zone (Figure 3.7; Table 3.3).

Changes in surface elevation in the basalts were fairly similar, at the mid- to the high tidal level, in the laboratory and in the field, although the expansion-contraction data in the field were collected from 7 TMEM stations representing a much greater range of rock properties than in the laboratory. There was little difference, however, between elevational changes at the high and mid-tidal levels in the field and laboratory (Figure 3.7): this is contrary to the laboratory data, which suggests that the fastest rates of downwearing are at the high tidal level (Table 3.3), but it is consistent with the lack of any clear spatial pattern in downwearing rates recorded at 20 TMEM stations, extending from a little below the mid-tidal level to the high tidal level, in the field (Trenhaile *et al.*, in press).

## 6.0 Conclusions

The main conclusions of this paper are as follows:

- (1) Intertidal rocks in eastern Canada contract, and occasionally expand, over short periods of time in response to tidal immersion and exposure.
- (2) The amount of contraction in argillites and basalts tends to increase with elevation within the intertidal zone and with the rate of surface downwearing, but there little or no relationship with rock hardness or with air temperature or humidity.



- (3) Changes in surface elevation are generally consistent from one tidal cycle to the next at the same points on the rock surface, but there are considerable variations between different points within TMEM stations over single tidal cycles.
- (4) Tidally induced variations in surface elevation are generally much lower than annual rates of surface downwearing owing to erosion. Short-term changes in elevation are often significant, relative to rates of downwearing, in argillites, however, especially in the upper intertidal zone, and in other cases where there are small amounts of erosion owing to the nature of the rock or to the measurement frequency.
- (5) Rock expansion and contraction may generate stresses that contribute to surface spalling and granular disintegration in some types of rock.
- (6) Contraction within the zone that is normally submerged twice a day by the tides is probably largely by alternate wetting and drying, rather than by salt crystallization.

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## **CHAPTER 4**

### **Project update**

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#### **1.0 Introduction**

The final chapter of this thesis briefly discusses some aspects of the study that have not been discussed in chapters 2 and 3. Chapter 2 deals with downwearing rates on shore platforms in eastern Canada, and chapter 3 is concerned with short term expansion and contraction of rock in the intertidal zone. The results of that work and the conclusions that can be drawn from it are based on the findings at the time of writing; therefore, chapter 4 will primarily focus on the updated laboratory downwearing rates and statistical analysis for four tidal simulators, with a comparative analysis between artificial sea water and de-ionized water for the first 28 months.

#### **2.0 Salt and fresh water weathering**

Wetting and drying is a fairly well known physical process that can cause rock to weather through the absorption and adsorption of water: however, there has been limited research to the efficacy of wetting and drying in the intertidal zone. Kanyaya and Trenhaile (2005) conducted a series of long-term experiments to determine the efficacy of wetting and drying in the intertidal zone using tidal simulators, which closely simulated natural tidal conditions. Since the conception of the project, two tidal simulators have been used to study the breakdown of rocks by wetting and drying in de-ionized water. The fresh water simulators started to be used in March 2003, beginning with a series of rocks composed of mainly carbonate, sandstone, igneous and metamorphic rocks, collected from quarries in southern Ontario by P.P Hudec at the University of Windsor. Shore platform samples of argillite, sandstone and basalt were added in June 2003. Since then, the Hudec collection containing 210 cores, have been subjected to tidal wetting and drying for 38 months (2300 cycles), and the shore platform samples, which consist of 225 sandstone cubes and 450 argillite and basalt cores, for 34 months (2050 cycles).

Two tidal simulators have also been used to study the breakdown of rocks in artificial sea water. These experiments, conducted in an identical fashion to the de-ionized water experiments, were designed to determine the effect of salt weathering in combination with tidal wetting and drying. The first salt tidal simulator began to be used in January 2004: this simulator, contained two sets of rocks, similar to those in the fresh water experiments. The first set of rocks consisted

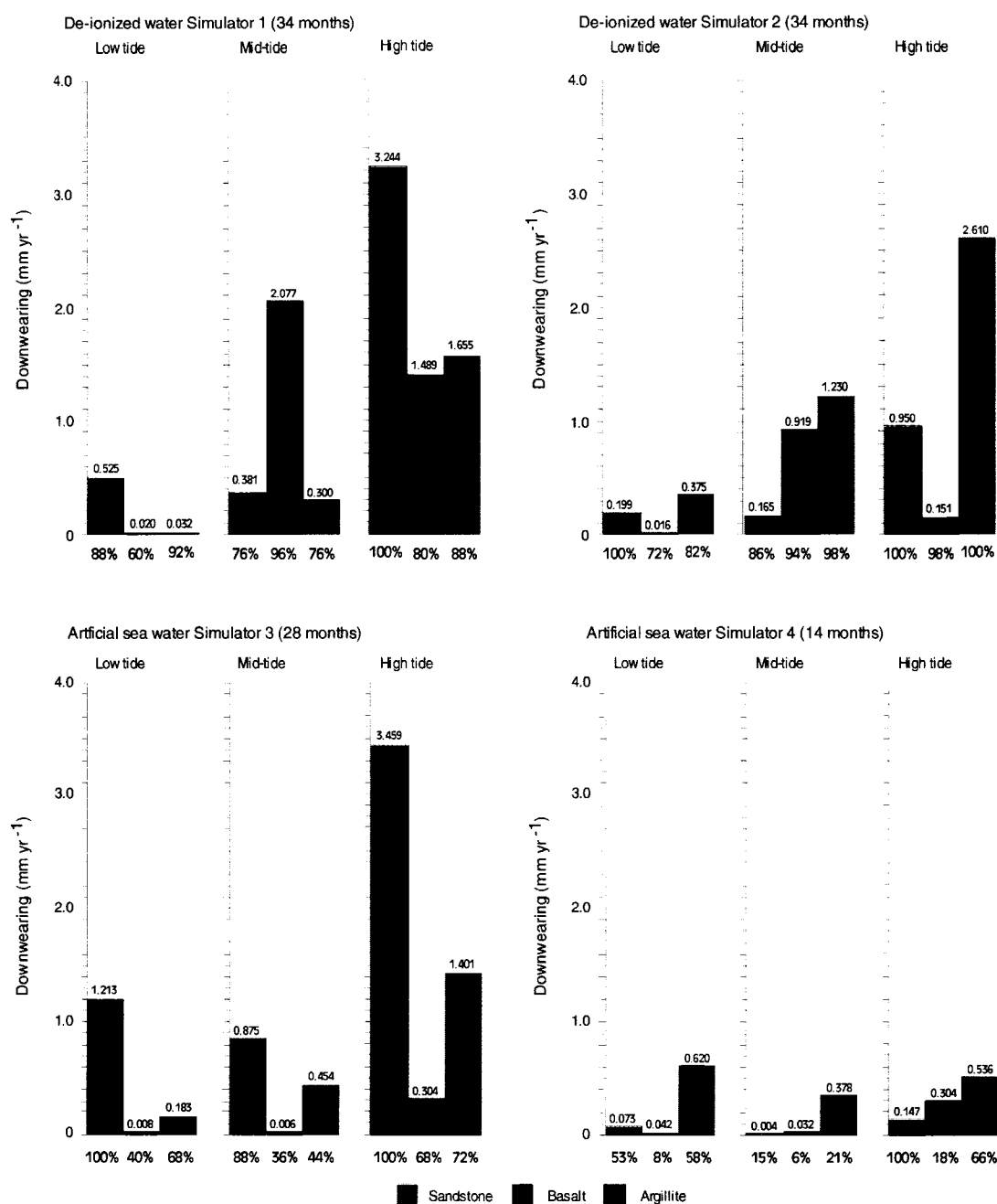
of 210 cores from the Hudec collection, and 225 cores and cubes from various rocks from the study shore platforms in eastern Canada. This experiment started much later than the fresh water experiments, and consequently, these rock samples have only, at the time of writing, been subjected to about 1700 tidal cycles over 28 months. A second salt water simulator was started in February 2005, using only rocks from eastern Canada. This simulator contains 150 basalt, 96 sandstone and 75 argillite cores: the rocks in this simulator have, at the time of writing, experienced 850 cycles over 14 months. The downwearing rates presented in this thesis are based on the results (and months noted above) at the time of writing. To compare the laboratory data with TMEM data from the field, core and cube breakdown values were converted into the equivalent rate of surface downwearing ( $D_r$ ) ( $\text{mm yr}^{-1}$ ) (see chapter 1, equation 1).

## 2.1 Breakdown rates in fresh water

The fresh water experiments have been operating for nearly three years. The data that have been collected demonstrate that there are significant differences in breakdown rates for each of the rock types from eastern Canada and for the rocks in the Hudec collection, as well as between the same rock types at different tidal levels (Fig. 4.1).

Although there are differences between breakdown rates in fresh water between the two tidal simulators (1 and 2), the experiments suggest that argillite is more susceptible to wetting and drying than the other rock types. This is evident in both tidal simulators. In simulator 1, nearly three quarters of the argillite cores at the low, mid and high tide levels have experienced some form of breakdown, with the greatest amount of downwearing ( $1.665 \text{ mm yr}^{-1}$ ) at the high tidal level. Simulator 2 exhibited nearly the same pattern over a 34 month period. In this case, 100% of the cores experienced breakdown at the high tidal level, resulting in a mean downwearing rate of  $2.61 \text{ mm yr}^{-1}$ .

Although simulators 1 and 2 have been operating for the same 34 month period, there are a few notable differences between rates and patterns of basalt breakdown in the two simulators. In simulator 1, the basalts at the mid-tidal level weathered more rapidly than their counterparts in simulator 2. In both simulators, 60 to 70% of the basalt cores at the low tidal level have shown negligible signs of breakdown, averaging less than  $0.020 \text{ mm yr}^{-1}$ , but there is a large increase in the rate of breakdown at the mid-tidal level, ranging from a mean of  $2.077 \text{ mm yr}^{-1}$  in simulator 1 and  $0.919 \text{ mm yr}^{-1}$  in simulator 2, respectively (Fig 1). These values decrease at the high tidal level to  $1.489 \text{ mm yr}^{-1}$  in simulator 1 and  $0.151 \text{ mm yr}^{-1}$  in simulator 2.



**Figure 4.1.** Downwearing rates measured over 34 months in de-ionized (simulators 1 & 2), and over 28 and 14 months (simulator 3 & 4, respectively) in artificial sea water. Negative values, caused by increased water retention, and possibly associated with surface swelling, were omitted from the analysis. The numbers listed beneath each column represent the percentage of each rock sample, at each simulated tidal level, that experienced downwearing.

Unlike the basalts, the sandstones show a general pattern of increased breakdown with elevation within the intertidal zone. Rates of breakdown at the low and mid-tidal levels are similar to each other in both simulators 1 and 2, and they are much lower than the rates at the high tidal level. Of the 25 sandstone samples at the high-tidal level in simulator 1, nearly all of them have shown signs of severe disintegration, and in some cases they have completely disintegrated, producing a downwearing rate of  $3.244 \text{ mm yr}^{-1}$  (Fig 4.1). Simulator 2 contains 50 sandstone samples at the high tidal level, all of which have experienced granular disintegration, although not to the same extent as in simulator 1. Most of the samples have remained intact, with the exception of a few that have split apart, yet none have been totally destroyed. Sandstone downwearing rates in simulator 2 were therefore lower than in simulator 1, with a mean value  $0.950 \text{ mm yr}^{-1}$  (Fig 4.1).

The Ontario rock cores from the Hudec collection were much less susceptible to alternate wetting and drying than the sandstone, argillite and basalt samples from eastern Canada (Table 4.1). These Ontario cores experienced mean downwearing rates ranging from  $0.00$  to  $0.18 \text{ mm yr}^{-1}$  at the high tidal level,  $0.00$  to  $0.148 \text{ mm yr}^{-1}$  at the mid-tidal level and  $0.00$  to  $0.136 \text{ mm yr}^{-1}$  at the low tidal level. Downwearing rates are dependent on the lithology of the rock, and the results suggest that the harder metamorphic and igneous rocks, comprised of diorite, nepheline, granite and gneiss, were much more resistant to the effects of wetting and drying than the softer sedimentary rocks, consisting of dolomite, limestone, sandstone and shale.

**Table 4.1.** Mean rates of downwearing ( $\text{mm yr}^{-1}$ ) using artificial sea water and de-ionized water over a 38 month period. (210 cores, 2300 cycles, 38 months). Hudec rock set.

Rock Type	High Tide		Mid Tide		Low Tide	
	Artificial Sea Water	De-ionized Water	Artificial Sea Water	De-ionized Water	Artificial Sea Water	De-ionized Water
Dolomite <sup>a</sup>	0.025	0.005	0.002	0.082	0.003	0.089
Dolomite <sup>b</sup>	+0.015	0.000	0.002	0.057	0.004	0.136
Dolomite <sup>c</sup>	+0.013	0.000	0.003	0.010	0.003	0.061
Dolomite <sup>d</sup>	0.045	0.003	+0.019	0.051	0.001	0.098
Sandstone <sup>a</sup>	0.036	0.008	0.012	0.000	0.0005	0.000
Sandstone <sup>b</sup>	0.009	0.003	0.000	0.017	0.001	0.006
Limestone	0.018	0.018	0.000	0.148	0.011	0.220
Shale	0.004	0.006	0.003	0.017	0.0004	0.032
Diorite <sup>a</sup>	0.029	0.002	0.0004	0.005	0.000	0.010
Diorite <sup>b</sup>	0.002	0.001	0.000	0.008	0.000	0.0008
Nepheline	0.003	0.011	0.0004	0.008	0.000	0.015
Granite	0.003	0.005	0.001	0.009	0.000	0.013
Gneiss	0.003	0.012	0.0006	0.003	0.000	0.003

Plus signs indicate gains in weight; losses in weight are unmarked

## 2.2 Breakdown rates in salt water

The two fresh water experiments have been operating continuously for the past 34 months; but the two salt experiments, have been ongoing for shorter and dissimilar periods of time. Of the two salt water simulators, only 3 has been in operation long enough to provide reasonably reliable data on breakdown rates in artificial sea water. Although simulator 4 has not been running long enough to make any definite conclusions, however, initial results suggest that the argillite samples may break down more than the other rocks from eastern Canada.

Rates of argillite downwearing in sea water increase with elevation in the intertidal zone (Fig. 4.1). Nearly three-quarters of the samples in simulator 3 have experienced breakdown at the high tide level, with a mean rate of  $1.401 \text{ mm yr}^{-1}$ . Mean breakdown rates are  $0.454 \text{ mm yr}^{-1}$  at the mid tide level and  $0.183 \text{ mm yr}^{-1}$  at the low tide level, respectively (Fig. 4.1).

The basalts experienced the slowest rates of breakdown in salt water. Some of the lowest downwearing rates occur at the low and mid tidal levels, averaging  $0.007 \text{ mm yr}^{-1}$  for simulator 3, and rising to a mean of  $0.304 \text{ mm yr}^{-1}$  at the high tidal level (Fig. 4.1).

Salt weathering, is much more effective on the red sandstones from Burntcoat Head than on the other rock types from eastern Canada. The fastest rate in simulator 3 was at the high tidal level, with a mean of  $3.459 \text{ mm yr}^{-1}$ . Mean sandstone breakdown rates at the low and mid tidal levels are  $1.213 \text{ mm yr}^{-1}$  and  $0.875 \text{ mm yr}^{-1}$ , respectively (Fig. 4.1). Almost all the sandstone cubes experienced erosion at the high and the low tidal levels over the 28 month period, and 68 % at the mid-tidal level.

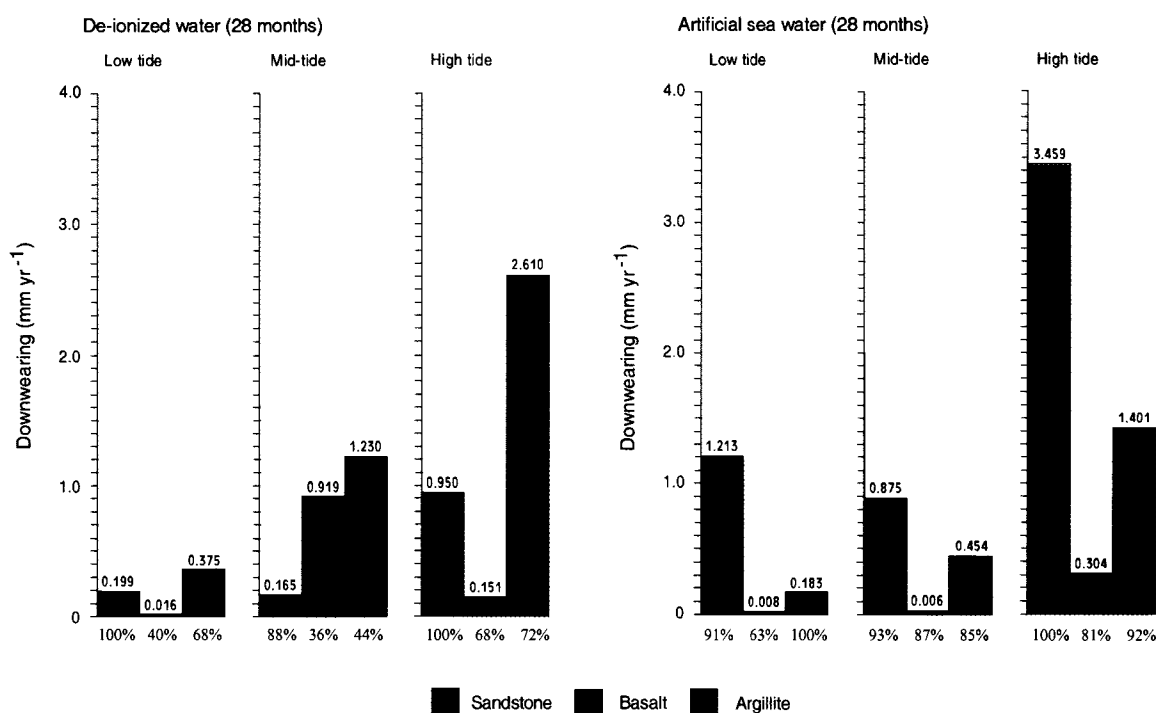
The Hudec collection has some of the same characteristics in salt water as in fresh water. The more durable rock types, such as diorite, nepheline, granite and gneiss have experienced little to no downwearing, and the less durable lithologies, such as dolomite, limestone, sandstone and shale, have only experienced slow breakdown. There are a few cases in some dolomite samples, where cores actually gained weight ( $+0.015 \text{ mm yr}^{-1}$  in extreme cases) after long exposure to tidal cycles (Table 4.1), possibly owing to salt accumulation within the rock.

## 2.3 Fresh and salt water comparisons

To compare downwearing rates between fresh and artificial sea water over equal periods of time, only data obtained over the first 28 months from simulators 1, 2 and 3 are used in this discussion. Mean downwearing rates in salt water are derived from a total of 25 samples of basalt, argillite and sandstone per tidal basin (225 samples in total). These saltwater data from



simulator 3 are compared with fresh water data (combination of simulators 1 and 2) from 75 basalt, argillite and sandstone cores and cubes per tidal basin (675 samples in total). In general, the results suggest that argillite is the most susceptible rock type in fresh water, whereas, sandstones are most susceptible in salt water (Fig. 4.2, Table 4.2). Furthermore, in both the fresh water and salt water experiments, downwearing rates tend to increase with elevation within the intertidal zone. Rocks in the salt water experiments are subjected to salt weathering (particularly salt crystallization in the voids) and alternate wetting and drying, and one might therefore expect to find that breakdown rates would be higher in salt than in fresh water. Higher downwearing rates in fresh than in salt water, however, in the argillites, in the basalts at mid-tide, and in some of the rocks in the Hudec collection, suggest that the presence of salts can inhibit rock deterioration in some way, possibly by holding loose fragments together: longer-term experiments will be needed to determine whether this is a temporary or permanent phenomenon.

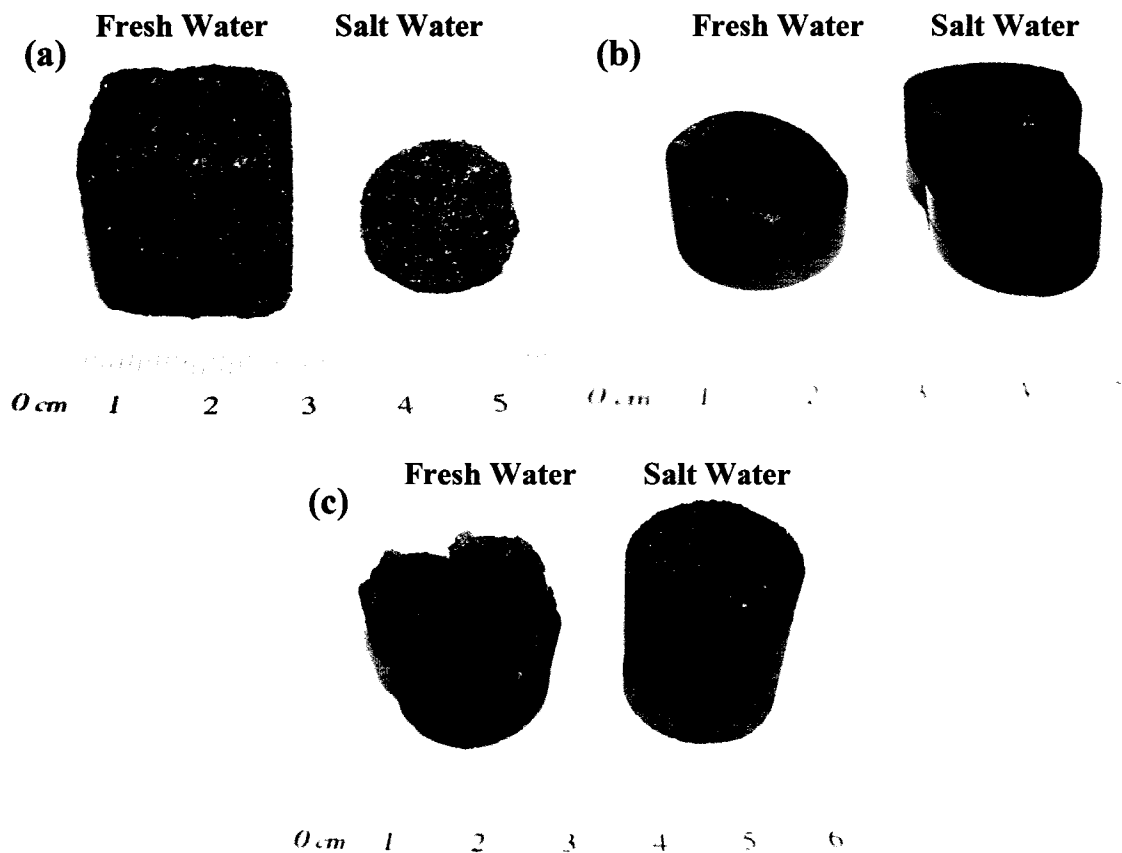


**Figure 4.2.** Comparative downwearing rates between artificial sea and de-ionized water, measured over 28 months. Negative values, caused by increased water retention, and possibly associated with surface swelling, were omitted from the analysis. The numbers listed beneath each column represent the percentage of each rock type sample that experienced downwearing.

Table 4.2. Descriptive statistics for downwearing rates between artificial sea water and de-ionized water over 28 months.

	De-ionized Water								
	Low Tide			Mid Tide			High Tide		
	Sandstone	Basalt	Argillite	Sandstone	Basalt	Argillite	Sandstone	Basalt	Argillite
Mean	0.200	0.016	0.375	0.165	0.919	1.230	0.950	0.151	2.610
Standard Error	0.063	0.005	0.096	0.045	0.145	0.141	0.181	0.043	0.164
Median	0.086	0.005	0.019	0.048	0.194	1.205	0.157	0.020	2.793
Mode	0.000	0.000	0.000	0.000	0.000	0.000	N/A	0.000	4.000
Standard Deviation	0.545	0.044	0.831	0.393	1.257	1.220	1.570	0.370	1.419
Variance	0.297	0.002	0.690	0.154	1.579	1.488	2.464	0.137	2.015
Kurtosis	48.424	48.100	5.552	32.731	1.074	-0.113	1.248	14.583	-0.719
Skewness	6.627	6.474	2.417	5.286	1.430	0.764	1.698	3.621	-0.694
Range	4.368	0.352	4.000	2.877	4.051	4.100	4.927	2.190	4.099
Minimum	0.000	0.000	0.000	0.000	0.000	0.000	0.014	0.000	0.000
Maximum	4.368	0.352	4.000	2.877	4.051	4.100	4.941	2.190	4.099
Sum	14.976	1.218	28.091	12.405	68.906	92.237	71.232	11.298	195.751
Count	75	75	75	75	75	75	75	75	75
Artificial Sea Water									
Mean	1.212	0.008	0.182	0.875	0.006	0.455	3.459	0.304	1.401
Standard Error	0.281	0.004	0.100	0.263	0.003	0.133	0.168	0.105	0.309
Median	0.494	0.000	0.007	0.248	0.000	0.000	3.829	0.047	1.120
Mode	N/A	0.000	0.000	0.000	0.000	0.000	4.178	0.000	0.000
Standard Deviation	1.407	0.020	0.501	1.316	0.017	0.663	0.841	0.527	1.547
Variance	1.981	0.000	0.251	1.732	0.000	0.440	0.707	0.277	2.394
Kurtosis	1.850	16.582	6.785	2.271	18.713	0.723	0.133	4.205	-0.882
Skewness	1.728	3.873	2.785	1.711	4.164	1.249	-1.014	2.141	0.806
Range	4.574	0.096	1.878	4.385	0.081	2.286	3.224	2.028	4.024
Minimum	0.118	0.000	0.000	0.000	0.000	0.000	1.276	0.000	0.000
Maximum	4.692	0.096	1.878	4.385	0.081	2.286	4.500	2.028	4.024
Sum	30.312	0.201	4.561	21.884	0.150	11.363	86.476	7.603	35.021
Count	25	25	25	25	25	25	25	25	25

The tidal simulation experiments suggest that rock types not only behave differently in fresh and salt water, but also that they behave differently at different tidal levels. Sandstones seem to be more susceptible to breakdown in salt than in fresh water (Fig 4.2), and they also begin to break down much earlier in salt than in fresh water. Although granular disintegration is the dominant mode of sandstone breakdown, there are some differences in the way they deteriorate in fresh and salt water. In particular, the sandstones tend to rapidly become spherical in salt water whereas they tend to weather more slowly in fresh water and thereby maintain their cubic form, albeit with rounded edges (Fig 4.3a). High sandstone breakdown rates in fresh water in simulator 1, which are similar to those in salt water from simulator 3, may be possibly attributed to the selection of a less resistant or weathered sandstone sample than that in simulator 2.



**Figure 4.3.** Breakdown characteristics of sandstone, argillite and basalt in artificial sea and fresh water.

Argillite breakdown characteristics are similar in salt and in fresh water environments (Fig 4.3b). Argillites mainly break down by splitting along the cleavage planes, particularly at the high tide level (Fig. 4.1). The basaltic cores in salt water remained essentially intact, although there was some pitting on the top of the cores. In fresh water, the basaltic cores eventually broke down into small, angular segments (Fig. 4.3c).

### **3.0 Statistical analysis: Analysis of variance**

Analysis of variance (ANOVA) was used to analyze the relationships between downwearing rates, tidal elevations, and rock types. ANOVA can be used to test or compare the means among two or more groups of observations. ANOVA is preferable to multiple t-tests because it reduces the number of calculations that would be required and the probability of making a type-I error: it does, however, have some limitations. Analysis of variance only shows that there is a significant difference between mean values, but it does not reveal where the significant differences are in respect to each group: this situation can be overcome by post hoc tests, in conjunction with the ANOVA results. In the present analysis there is only one factor (one-factor ANOVA), which is the tidal elevation. Other factors such as rock type or densities (two-factor ANOVA), were investigated, but this analysis was abandoned due to the heteroscedasticity within the groups.

ANOVA was performed on rocks of the same lithology from each of the tidal basins within the same simulator. The test was applied to the two fresh water and two artificial sea water simulators, regardless of the number of samples and the duration of the experiments. Nevertheless, the initial results indicate that there are significant differences between breakdown rates at the low, mid- and high tidal levels for the same type of rocks (Table 4.3), in both salt and fresh water (Table 4.4). In simulator 1, all of the null hypothesis, which state that there are no significant differences among mean downwearing rates and tidal range, were rejected, as well as the low and mid-tide results in simulator 2, except for the sandstone samples. This suggests that breakdown rates in simulator 2 are similar in the sandstones at the low, mid- and high tidal levels. There were also significant differences between rock breakdown rates at different tidal levels for all of the rock types in simulator 3. Comparison of the basalt and argillite means at different tidal elevations in simulator 4 suggest that they are statistically similar, whereas the sandstone means are significantly different. The lack of any significant differences between rock breakdown rates at different tidal levels for the basalt and argillite samples can probably be explained by the fairly short length of time that simulator 4 has been operating, and the correspondingly short time for any breakdown to occur.

### **3.1 Post hoc comparisons: The Scheffe Test**

Post hoc comparisons are generally performed only after obtaining a significant F value in the ANOVA analysis. The Scheffe Test can be used to determine which cell means differ from other cell means: this is determined by calculating the F value for the difference between the means of two cells. The specific cell can be interpreted as the tidal level, which is the primary factor in the ANOVA and Scheffe Test. The Test was used to compare low to mid, low to high and mid to high values for each of the basalt, argillite and sandstone samples in a particular simulator. F values are high if the difference in downwearing rates between cell values is significant, and low if they are not significant. Differences in sandstone F values, and consequently downwearing rates, between the mid and high tidal levels are high in all four simulators (Tables 4.5 and 4.6), whereas they are greatest between the low and mid tidal levels in basalt. Differences in the F values and downwearing rates are very high between the low and high tidal levels in the argillite (Fig. 1).

### **3.2 Statistical comparisons between fresh and salt water**

The t-test is a useful tool for comparing the means of two groups, but it is not an effective statistical procedure in situations calling for the comparison of three or more groups. To determine if fresh water and salt water means are statistically different from each other, a simple t-test was employed to compare downwearing rates at different tidal elevations.

Sandstone was the only rock type in which there was significant differences in downwearing rates between salt and fresh water at all tidal elevations. There were also differences between argillite downwearing in fresh and salt water at the mid- and high tidal levels and at the mid-tidal level in basalts (Table 4.7).

**Table 4.3.** ANOVA Statistical Analysis for Tidal Simulators 1 through 4.

Summary						ANOVA						Significance
Simulator	Groups	Count	Sum	Mean	Variance	Sum of Squares "SS"	MS bet/with groups	df Total	F-value	P-value	F-critical	* Reject Null
Simulator 1 De-ionized Water	Low Tide Basalt	25	0.50	0.02	0.0049	176.19	28.05/1.66	74	16.82	1.01E-06	3.12	*
	Mid Tide Basalt	25	51.91	2.07	2.7350							
	High Tide Basalt	25	37.22	1.49	2.2635							
	Low Tide Argillite	25	0.79	0.03	0.0028	120.80	18.95/1.15	74	16.45	1.3E-06	3.12	*
	Mid Tide Argillite	25	7.47	0.30	0.4862							
	High Tide Argillite	25	41.39	1.65	2.9654							
	Low Tide Sandstone	25	13.13	0.53	1.0122	243.48	65.02/1.57	74	41.27	1.14E-12	3.12	*
	Mid Tide Sandstone	25	9.52	0.38	0.3105							
	High Tide Sandstone	25	81.09	3.24	3.4037							
Simulator 2 De-ionized Water	Low Tide Basalt	50	0.88	0.01	0.0005	127.59	17.81/0.62	149	28.46	3.56E-11	3.06	*
	Mid Tide Basalt	50	57.43	1.14	1.5910							
	High Tide Basalt	50	12.63	0.25	0.2854							
	Low Tide Argillite	50	37.22	0.74	1.0824	337.16	81.37/1.18	149	68.58	9.15E-22	3.06	*
	Mid Tide Argillite	50	92.48	1.85	1.5593							
	High Tide Argillite	50	164.42	3.28	0.9179							
	Low Tide Sandstone	50	6.61	0.13	0.0155	29.81	0.23/0.19	149	1.19	0.301	3.06	
	Mid Tide Sandstone	50	6.51	0.13	0.3959							
	High Tide Sandstone	50	12.53	0.25	0.1870							

**Table 4.3. Cont'** ANOVA Statistical Analysis for Tidal Simulators 1 through 4.

Summary						ANOVA						Significance
Simulator	Groups	Count	Sum	Mean	Variance	Sum of Squares "SS"	MS bet/with groups	df Total	F-value	P-value	F-critical	* Reject Null
Simulator 3 Artificial Sea Water	Low Tide Basalt	25	0.20	0.008	0.0004	8.14	0.73/0.09	74	7.94	0.0007	3.12	*
	Mid Tide Basalt	25	0.14	0.005	0.0002							
	High Tide Basalt	25	7.60	0.304	0.2773							
	Low Tide Argillite	25	4.56	0.182	0.2510	94.49	10.22/1.02	74	9.94	0.0001	3.12	*
	Mid Tide Argillite	25	11.36	0.454	0.4399							
	High Tide Argillite	25	35.02	1.400	2.3940							
	Low Tide Sandstone	25	30.31	1.212	1.9806	204.71	49.31/1.47	74	33.47	5.26E-11	3.12	*
	Mid Tide Sandstone	25	21.88	0.875	1.7319							
	High Tide Sandstone	25	86.47	3.459	0.7071							
Simulator 4 Artificial Sea Water	Low Tide Basalt	50	2.10	0.042	0.0878	4.37	0.02/0.02	149	0.88	0.41	3.06	
	Mid Tide Basalt	50	0.16	0.003	0.0003							
	High Tide Basalt	50	0.11	0.002	6.2E-05							
	Low Tide Argillite	24	14.87	0.619	0.7869	47.94	0.38/0.68	71	0.56	0.57	3.13	
	Mid Tide Argillite	24	9.04	0.376	0.5721							
	High Tide Argillite	24	13.39	0.558	0.6920							
	Low Tide Sandstone	32	2.34	0.073	0.0159	1.05	0.16/0.007	95	21.30	2.41E-08	3.09	*
	Mid Tide Sandstone	32	0.11	0.003	9.19E-05							
	High Tide Sandstone	32	4.71	0.147	0.0072							

Summary						ANOVA						Significance
Simulator	Groups	Count	Sum	Mean	Variance	Sum of Squares "SS"	MS bet/with groups	df Total	F-value	P-value	F-critical	* Reject Null
28 months Artificial Sea Water	Low Tide Basalt	25	0.20	0.008	0.0004							
	Mid Tide Basalt	25	0.14	0.005	0.0002	8.14	0.73/0.09	74	7.94	0.0007	3.12	*
	High Tide Basalt	25	7.60	0.304	0.2773							
	Low Tide Argillite	25	4.56	0.182	0.2510							
	Mid Tide Argillite	25	11.36	0.454	0.4399	94.49	10.22/1.02	74	9.94	0.0001	3.12	*
	High Tide Argillite	25	35.02	1.400	2.3940							
	Low Tide Sandstone	25	30.31	1.212	1.9806							
	Mid Tide Sandstone	25	21.88	0.875	1.7319	204.71	49.31/1.47	74	33.47	5.26E-11	3.12	*
	High Tide Sandstone	25	86.47	3.459	0.7071							
28 months De-ionized Water	Low Tide Basalt	75	1.21	0.016	0.0019							
	Mid Tide Basalt	75	68.90	0.918	1.5794	162.69	17.78/0.57	224	31.05	1.29E-12	3.03	*
	High Tide Basalt	75	11.29	0.150	0.1366							
	Low Tide Argillite	75	28.09	0.374	0.6903							
	Mid Tide Argillite	75	92.24	1.229	1.4877	501.09	95.42/1.39	224	68.27	7.74E-24	3.03	*
	High Tide Argillite	75	195.75	2.610	2.014							
	Low Tide Sandstone	75	14.97	0.199	0.2968							
	Mid Tide Sandstone	75	12.40	0.165	0.1541	245.17	14.74/0.97	224	15.17	6.69E-07	3.03	*
	High Tide Sandstone	75	71.23	0.949	2.4639							



**Table 4.5.** Scheffe post hoc comparisons between cells, simulators 1 through 4.

	Simulator 1 De-ionized Water (34 months)			Simulator 2 De-ionized Water (34 months)			Simulator 3 Artificial Sea Water (28 months)			Simulator 4 Artificial Sea Water (14 months)		
Comparisons	Basalt	Argillite	Sandstone	Basalt	Argillite	Sandstone	Basalt	Argillite	Sandstone	Basalt	Argillite	Sandstone
Low - Mid	10.5662	0.2589	0.0549	17.0374	8.5803	0.0001	22.8297	5.4054	0.0228	0.4282	0.3456	3.3259
Low - High	5.3909	9.5410	19.5427	0.7362	45.4587	0.5859	4.6032	39.6542	9.1073	0.4495	0.0221	3.7811
Mid - High	0.8625	6.6561	21.6709	10.6904	14.5396	0.6044	6.9302	15.7783	10.0417	0.0002	0.1928	14.1997

**Table 4.6.** Scheffe post hoc comparisons between cells, salt and fresh water.

	Artificial Sea Water (28 months)			De-ionized Water (28 months)		
Comparisons	Basalt	Argillite	Sandstone	Basalt	Argillite	Sandstone
Low - Mid	0.0002	0.2999	0.3214	17.7792	6.5429	0.0151
Low - High	3.9408	6.0149	14.2739	0.3942	44.6980	7.2382
Mid - High	3.9952	3.6284	18.8794	12.8782	17.0383	7.9151

**Table 4.7.** T-test significance differences between rock downwearing in salt and fresh water

	Basalt	Argillite	Sandstone
Low Tide			*
Mid Tide	*	*	*
High Tide		*	*

## REFERENCES

Kanyaya, J.I. and Trenhaile, A.S., 2005. Tidal wetting and drying on shore platforms: an experimental assessment. *Geomorphology*, 70: 129-146.

## APPENDIX A: DECLARATION OF CO-AUTHOR CONTRIBUTIONS

I acknowledge and give personal consent to the use of information in the following manuscripts, one of which is in press, and the second has been submitted in the M.Sc thesis of Neil James Porter.

1. The manuscript entitled "Shore Platform Processes In Eastern Canada" is in press with the journal *Geographie Physique et Quaternaire*. The paper is co-authored by Trenhaile, A.S., Porter, N.J. and Kanyaya, J.I.
2. The manuscript entitled "Short-term rock expansion and contraction in the intertidal zone" was submitted to the journal *Earth Surface Processes and Landforms*. The paper is co-authored by Porter, N.J., and Trenhaile, A.S.

My intellectual contribution to the work reported in these manuscripts was the formulation of the research plan to study "Shore platform processes in eastern Canada" and to assist in sampling collecting. The study was directed by Dr. A.S. Trenhaile, who also contributed to the data interpretation and drafting of the manuscripts. As Mr. Porter's thesis supervisor, my financial contribution to the funding of the work carried out in eastern Canada and at the University of Windsor was 100% from my Natural Sciences and Engineering Research Council of Canada and research grants.

Signed: Alan S. Trenhaile Date: 21 Sept. 2006

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